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A COMBINED HAZARD INDEX FIRE TEST METHODOLOGY FOR AIRCRAFT CABI--ETC(U)

APR 82 H H SPIETH, J G GAUME, R E LUOTO

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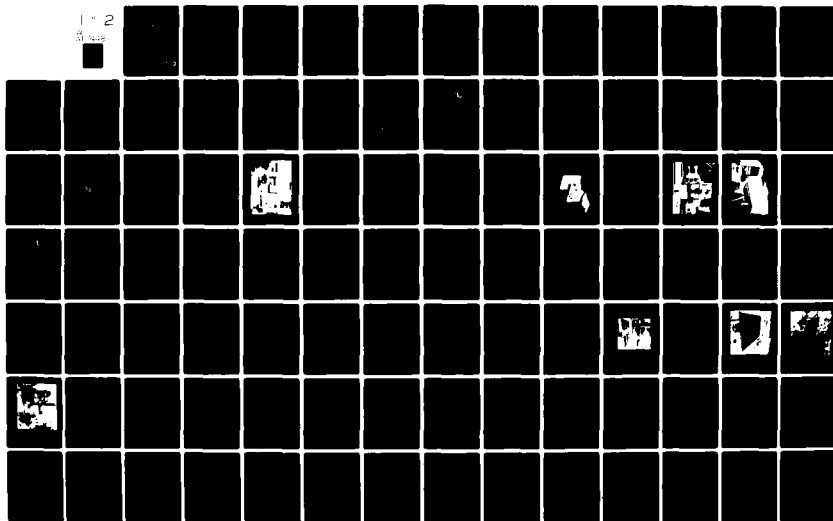
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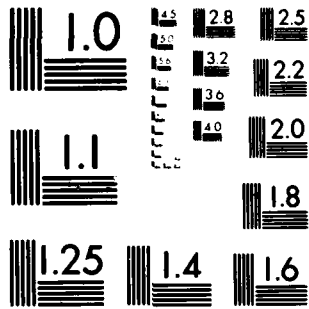
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A Combined Hazard Index Fire Test Methodology for Aircraft Cabin Materials - Volume I

AD A117448

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Final Report

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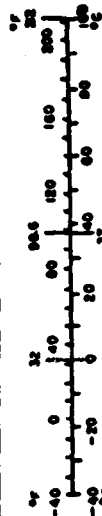
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yds	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
sq in	square inches	6.5	square centimeters	cm ²
sq ft	square feet	0.09	square meters	m ²
sq yds	square yards	0.8	square meters	m ²
sq mi	square miles	2.6	square kilometers	km ²
acres	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	4.5	kilograms	kg
short tons (2000 lb)	short tons	0.9	metric tons	t
VOLUME				
qt	quarts	1	liters	l
pt	pints	0.5	liters	l
cup	cups	0.24	liters	l
gal	gallons	3.8	liters	l
barrel	barrels	160	liters	l
cu ft	cubic feet	0.028	cubic meters	m ³
cu yd	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 cm exactly. For other exact conversions and more detailed tables, see NIST Spec. Publ. 280, Guide for SI Units and Measures, May 1975, SD Catalog No. C13 19-200.

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
km	kilometers	1.1	yards	yds
		0.6	miles	mi
AREA				
sq cm	square centimeters	0.16	square inches	sq in
sq m	square meters	1.2	square yards	sq yds
sq km	square kilometers	0.4	square miles	sq mi
hectares (10,000 m ²)	hectares	2.5	acres	acres
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
tonnes (1000 kg)	tonnes	1.1	short tons	short tons
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	1.06	quarts	qt
kl	kiloliters	0.26	gallons	gal
cu m	cubic meters	35	cubic feet	cu ft
cu km	cubic kilometers	1.3	cubic yards	cu yd
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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16. Abstract This report describes a laboratory test method and the modeling of the resultant data to produce a means of ranking aircraft cabin materials for the combined hazards produced in a survivable post-crash fire. Ranking is based on reducing each hazard accumulating in a cabin during a 5-minute crash fire scenario to the common denominator of a passenger escape time. Combined Hazards Index (CHI) is expressed as the number of seconds of scenario burn time at which the sum of the fractional hazards doses reaches an escape limit. All data was obtained using a computer-augmented Ohio State University Calorimeter modified to measure the major combustion gases in addition to heat and smoke as a material burns. A computerized fire analysis model was developed to predict cabin environmental hazards from the laboratory data. A human survival model relating short term hazard dose to incapacitation time was incorporated in this program. The changing cabin environment was compared continuously with the human survival model limits to calculate the unaided escape time ranking for each material. Four typical cabin panels of different composition were tested under similar fire threat conditions in laboratory and in a 12 x 40 ft Cabin Fire Simulator (CFS). The large scale tests were used to compare the measured cabin environment with the environment predicted by the fire analysis computer program, and to establish CHI values for the test materials. The combined hazards analysis system developed during this study provides extensive and repeatable data for heat, smoke and toxic gases to rank materials based on personnel hazards.			
17. Key Words Aircraft Cabin Fire Safety Aircraft Interior Materials Combined Fire Hazards Fire Test Methodology Fire Measurements		18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161	
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PREFACE

This research program was conducted and the report prepared by the Douglas Aircraft Company, a Divisional Company of the McDonnell Douglas Corporation, under Contract No. DOT-FA77WA-4019 for the Federal Aviation Administration of the Department of Transportation. Until his retirement Mr. Robert C. McGuire was Program Manager for the Federal Aviation Administration. He was succeeded by Mr. Constantine P. Sarkos at the Federal Aviation Administration Technical Center.

The report is divided into two parts for those with different needs. Part I describes the new direction taken from the then existing technology to provide a common denominator for flammability, smoke, (visibility) and toxicity; development of the methodology and test equipment necessary to produce a combined index; validation by full-scale burn tests; and recommendation of a method for ranking materials from the several approaches in which the concept can be applied. Part II is for those who wish to delve deeper into the details of construction. It includes operation of test equipment, derivation and solution of equations, derivation and selection of human hazard limits, writing and listing of computer programs and examples of output data.

The authors wish to acknowledge the valuable assistance of H. C. Wilkinson, Engineer in charge of the CFS large scale testing at the McDonnell Douglas Astronautics Division, his crew of technicians, and N. R. Radke for his support in computer control and data processing of the large scale tests. Important contributions were made by K. J. Schutter, Douglas Aircraft Company Interiors Engineering, who coordinated the later testing in the CFS, acting as the test conductor. W. B. Engel, P. T. Lally, G. R. Bonnar, R. C. Wade, and G. W. Birrer, from Douglas Aircraft Company, Materials & Process Engineering gave valuable assistance in the setup, calibration, and operation of all gas analysis equipment during the CFS tests. These individuals also deserve recognition for their timely and careful microchemical analyses of hundreds of batch gas samples collected during the program. Mr. Sheng N. Lee deserves special commendation for his contributions in improving or writing the computer programs needed for successful data processing and evaluation. R. J. Sutton, Principal Technical specialist - Advanced Programs, and E. L. Weiner, Engineering Contract Administrator, made important contributions to the program.

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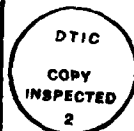


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ACRONYMS, ABBREVIATIONS AND INITIALISMS

A	Area
ADAS	Automatic Data Acquisition System
Adh.	Adhesive
ASTM	American Society for Testing and Materials
Av. RSD%	Average Relative Standard Deviation, Percent
Btu/ft² sec	Heat Flux, British Thermal Units per Square Foot per Second
C	Concentration (also a conversion factor)
CA (I, K)	Array Defining Flow Coefficients Between Zones
C_{air}	Concentration of O ₂ in Air, 20.93%
C_t	Depleted Concentration of O ₂ at any time, %
C_{co}	Concentration of Carbon Monoxide
CFS	Cabin Fire Simulator (Figure 1)
CHAS	Combined Hazards Analysis System
CHI	Combined Hazards Index (Equivalent to Escape Time)
CHx, HCx	Combustible Gases, Also Unburned Hydrocarbons
CO	Carbon Monoxide
COHb	Carboxyhemoglobin (as % blood saturation)
CO₂	Carbon Dioxide
COCl₂	Carbonyl Chloride
Cp	Specific Heat
C₁	Intercept of a Regression Line
C₂	Slope of a Regression Line
D	Distance Between a Light Source and an Observer, Feet
DACFIR	University of Dayton Aircraft Fire Computer Program
DATTAP	CHAS data on Fortran Fire Analysis Program Tape
Di	Dose of Toxic Gas Resulting in Incapacitation
DIFFEQ	Differential Equations Program for Calculating Rate of Change of all Variables (Subroutine)
DTP	Differential Thermopile
E	Exit Sign Light Illuminance at Observer's Eye
ESTI	Subroutine in Computer Program Calculates Fractional Doses and CHI
ET	Escape time (Egress Time from a Cabin)
FACP	Fortran IV Fire Analysis Computer Program
FD	Fractional Doses of Measured Hazard
GPIB	General Purpose Interface Bus
GRR	Gas Release Rate
G.S.	Gas Sampling by Syringe Method
HBr	Hydrogen Bromide
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HF	Hydrogen Fluoride
HRR	Heat Release Rate

ACRONYMS, ABBREVIATIONS AND INITIALISMS (Cont'd)

(HL) ₅	Five Minute Hazard Limit
HP-ADAS	Hewlett-Packard Automatic Data Acquisition System
H ₂ S	Hydrogen Sulfide
I	Zone Number in Computer Program, also Intensity of Light Source in Candela
IBM	International Business Machines (Computer)
K	Number of a Zone in an Array Connected to Zone I for Each of the Six Sides
KADL	Array Providing a Heat Transfer Between Zones in the.CFS
K _{1,2,3,n}	Derived Constant Used to Calculate Fractional Effective Doses of Hazards
LD ₁ , LD ₅₀ , etc.	Lethal Dose of a Toxic Substance Needed to Kill 1, 50, etc., Percent of Test Animals
LC ₅₀	Lethal Concentration Killing 50 Percent of Test Animals
Mass	Weight
MATS	Multiple Animal Test System
MBTH	3-Methyl-2-Benzothiazoline Hydrazone
MFD	Mixture Fractional Effective Dose
MW	Molecular Weight
MLT	Mass Loss Transducer (Figure 5)
NH ₃	Ammonia
NO _x	Oxides of Nitrogen
O ₂	Oxygen
P	Pressure, Also an Array Defining the P (I,K) Interconnections Between Zones (Computer Program)
PVF	Polyvinylfluoride (Decorative Coating Material)
PVC	Polyvinylchloride (Decorative Coating Material)
Pk SMO	Peak SMOKE Release Rate
Pk HRR	Peak Heat Release Rate
ppm	Parts per Million
Q ₀	Statistically Derived Proportionality Constant Related to Number of Calories of Heat Absorbed by the Human Body Before Collapse.
R	Correlation Coefficient
RCHO	Total Aldehydes (as formaldehyde)
RMV	Respiratory Minute Volume
RSD	Relative Standard Deviation
R ²	Coefficient of Determination
RUNGU	Runge Kutta Technique for Numerical Integration of Differential Equations (Subroutine)

ACRONYMS, ABBREVIATIONS AND INITIALISMS (Cont'd)

SATS	Single Animal Test System
SSU	Standard Smoke Unit (of S.M.O.K.E.)
S.M.O.K.E.	Standard Metric Optical Kinetic Emission (of smoke)
SO ₂	Sulfur Dioxide
SRR	Standard S.M.O.K.E. Release Rate Units (same as SSU)
t	Time
T	Temperature (also light transmission)
Td	Time to Death
Ti	Time to Incapacitation
TLV	Threshold Limit Value
T _o	Ambient Temperature
T _c	Time to Thermal Collapse (humans)
V	Volume, also Human Breathing (ventilation volume) Rate
V ₁	Valve Isolating Animal Test Chamber in CHAS/SATS
W	Weight
W _o /S _x	Without Animal Test Subject
W/S _x	With Animal Test Subject
Y _c	Char Yield

FIRE ANALYSIS COMPUTER PROGRAM SYMBOLS

a	Thermal Diffusivity, Ft ² /hr
A _f	Flame Area, Ft ²
AP	Area of Burning Panel, Ft ²
C _p , C _s	Specific Heat, Btu/lb. °F
h _a	Convective Heat Transfer Coefficient
h _e	Film Coefficient, Btu/hr. Ft ² °F
h _r	Radiant Heat Transfer Coefficient
k	Thermal Conductivity, Btu/hr Ft °F
L	Half Thickness, Ft
Ma	Weight of Air in a Zone, lb.
Mi IN	Mass Flow Rate of Gas into Zone or Compartment, lb/sec
Mi OUT	Mass Flow Rate of Gas Out of Zone or Compartment, lb/sec
Mi	Weight of Each Gas, lb

ACRONYMS, ABBREVIATIONS AND INITIALISMS (Cont'd)

P	Pressure, lb/ft ²
P _i	Partial Pressure of Each Gas (i) in Mixture, lb/ft ²
Q	Total Heat Flux per Unit Storage Area, Btu/hr, ft ²
R ₁	Gas Constant
RHO	Density of Gas Mixture, lb/ft ³
S ₁	Instantaneous Smoke Concentration Flowing into a Zone, "Particles"/ft ³
S ₂	Instantaneous Smoke Concentration Flowing out of a Zone, "Particles"/ft ³
S _{IN}	S.M.O.K.E. Flow into a Zone/ft ²
S _{OUT}	S.M.O.K.E. Flow out of a Zone/ft ²
θ	Time, hr
T _a	Temperature of Air, °F
T _{so}	Initial Surface Temperature, °F
T	Radiation View Factor
τ	Time, sec
V	Volume, ft ³
WM	Weight Flow Rate of Gas Mixture, lb/sec

EXECUTIVE SUMMARY

INTRODUCTION

This program accomplished the development and demonstration of techniques, procedures, and equipment needed to rank transport aircraft interior materials, as identified in Federal Air Regulation 25.853, for their total combustion hazards. The materials ranking method is called the "Combined Hazard Index" (CHI).

The CHI is expressed as the number of seconds of a crash fire scenario burn time available for passengers to escape from a cabin in which an interior material is involved in fire.

By this definition, escape time becomes the common denominator relating the quantities (doses) of smoke, toxic gases, and heat (temperature) accumulating within a cabin prior to passenger incapacitation. The incapacitation levels for each of the fire hazards considered was based on an analysis of available data taken from the literature. The CHI is calculated for a fixed cabin location, a specific cabin size and a given area of material subjected to a heat flux setting representative of a post-crash cabin fire.

Four large area cabin panels were selected to represent a wide range of typical constructions. The first was a wide-body honeycomb sandwich panel, of a phenolic-Nomex[®] core, fiberglass/modified phenolic faces and polyvinylfluoride (PVF)/polyvinylchloride (PVC) decorative covering on both sides, and was used for galley and lavatory walls. The second was an acoustic ceiling panel with a PVF/phenolic fiberglass perforated face, bonded to a fiberglass filled Nomex[®] honeycomb core and having a phenolic/fiberglass backface. The third panel was a 1958 design, using wood veneer facing and self-extinguishing paper honeycomb core. The fourth panel was identical in construction to panel 1, except for the use of epoxy resin instead of modified phenolic.

METHODOLOGY

CHI TEST

Testing a material to determine a CHI involved the following steps:

1. A single laboratory burn test produced all the necessary data including release rate measurements of heat, smoke, and various toxic gases. Except for the analysis of several gases made after the test, the data was recorded and converted to proper engineering units on a computerized automatic data acquisition system with the capability of also plotting hazard release rate history curves.

2. A Fire Analysis Computer Program (FACP), using data input from the laboratory test, mathematically modeled the growth in fire hazards with a hypothetical cabin enclosure. The program calculated and printed out (a) cabin hazards concentrations versus time, (b) fractional effective dose histories of each hazard expressed as the ratio of cabin hazard dose to the incapacitation dose, and (c) the burn time at which the summed fractional doses equaled one (100%). The latter defined the CHI for the material.

LABORATORY EQUIPMENT

The cornerstone of the CHI methodology is the laboratory test equipment, which is a modified version of the heat release rate calorimeter developed by E. E. Smith at Ohio State University. The original calorimeter realistically exposes a specimen to radiant heat and an ignition flame, and provides for the release rate measurements of heat and smoke. Additional outstanding features of this apparatus include: capability to vary heat flux level, measurement of hazard release rate histories (extremely important in aircraft crash fire environment where time is a critical parameter), and capability of changing specimen orientation (vertical or horizontal). A number of major modifications were made to the chamber during the CHI program, most notably for the measurement of gas emissions. Commercial analyzers were installed to continuously measure the following gases: carbon monoxide (CO), hydrogen cyanide (HCN), carbon dioxide (CO₂), oxygen (O₂), nitrogen oxides (NO_x) and total hydrocarbons (HC_x). Additional known species produced during the combustion of aircraft materials are analyzed from batch samples taken during the test [e.g., hydrogen fluoride (HF), hydrogen chloride (HCl)]. For developmental purposes, a mass loss transducer was added to the test specimen injection mechanism to record real time weight loss, and an animal (rat) test chamber was used to monitor toxicological response to the combustion products. Provisions were made for calibration of each of the measurements. All real time data were recorded using a minicomputer data acquisition and processing system. The complete test apparatus, as shown in the schematic diagram, was designated the Combined Hazard Analysis System (CHAS/Single Animal Test System (SATS). Replicate tests conducted on aircraft materials demonstrated that the CHAS/SATS produced repeatable results.

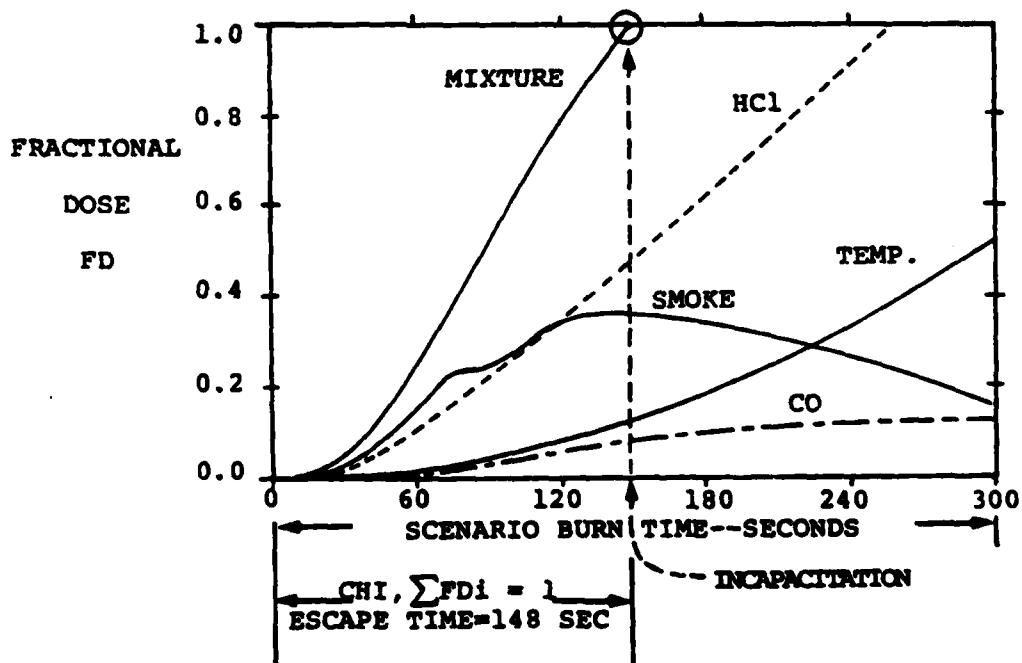
COMPUTER PROGRAM

The FACP solves four basic differential equations for smoke, air temperature, compartment wall temperature and gas partial pressure. The FACP was written in two versions. One divides the cabin into 20 zones and continuously calculates the transient hazard concentration and wall temperatures. This permits a realistic appraisal of the hazards produced by a single material in a ventilated or nonventilated compartment. Although the computer program continuously prints out the hazard levels in all zones, a specific CHI point was selected at 5 feet 6 inches above the floor and at the nearest survivable approach to the fire. The second version was a one-zone model simulating a section of fuselage with a well-mixed environment; this version requires less computer time. It retains the volume concept needed to calculate instantaneous doses and time to incapacitation, but loses the realism of a stratified cabin hazard environment.

Smoke was considered a hazard only as it affects the visibility of an illuminated exit sign or open door. In this concept, smoke slows occupant escape time and prolongs exposure to the temperature and gas hazards. A smoke hazard limit curve was derived assuming that an observer can see an exit sign 100 feet away when smoke transmittance is 93%, whereas in the opposite extreme, it was assumed that the unimpeded crawl time from the farthest seat to the nearest exit, in complete darkness, was 15 seconds.

The fractional "effective" dose FD_g , for smoke was the selected minimum escape time (15 seconds) divided by an escape time based on visibility in the smoke-filled cabin. The fractional "effective" dose for smoke is not a cumulative dose as are the other hazards and will decrease with decreasing smoke.

Using a method similar to one employed in industrial toxicology, the fractional "effective" doses (FD's) for each hazard were calculated and plotted individually as well as for the mixture. It was assumed that the mixture fractional "effective" dose was equal to the sum of the fractional "effective" doses for each hazard. As shown in the following FD plots, representative of a material combustion product mixture, incapacitation occurs at the scenario burn time when the mixture fractional dose becomes equal to 1 (100% of limit). This point in time defines the CHI for the material. The test materials were ranked directly by the relative CHI values in seconds of escape time. Better materials gave higher CHI values.



CABIN FIRE SIMULATOR

A 12 x 40 foot cabin fire simulator (CFS) was used to burn panels of the same materials tested in the CHAS to develop the FACP and demonstrate its

HAZARD ANALYSIS

predictive capability. The CFS was instrumented with thermocouples and smoke photometers in many locations as described in the report. Gases were monitored at the CHI point and at the cabin air exhaust. Six rat cages were placed at various locations. A radiant heat source was mapped with calorimeters to select power settings for a fixed specimen plane distance to have uniform 2.2, 3.08 and 4.41 Btu/ft²sec (2.5, 3.5 and 5 watts/cm²) heat fluxes to duplicate that of the laboratory tests. In each run a 4 x 6 foot test panel (one of four different types) was clamped to a four-bar linkage frame restrained by a thermally shielded load cell to measure mass loss. Multiple ignition flames were pivoted to impinge across the bottom of the panel for each test.

RESULTS

The ranking comparisons of the four panels tested during the program reflected by CHAS/SATS, the animals used in the CFS, and the relative CHI values base on the 20-zone and 1-zone FACP's are summarized in the following table.

SUMMARY OF CHI RELATIVE RANKINGS FOR ALL MATERIALS BY THE
CHAS/SATS, FACP AND CFS ANIMALS

HEAT FLUX	TEST	PHENOLIC PANEL 1	CEILING PANEL 2	WOOD VENEER PANEL 3	EPOXY PANEL 4
4.41 BTU PER FT ² SEC	FACP-CHI 20 ZONE	1	2	4	3
	1 ZONE	2	1	4	3
	ANIMALS SATS	1	2	3	4
	CFS	1 *	3 *	4	2 *
	ANALYTICAL CHAS	2	1	4	3
3.08 BTU PER FT ² SEC	FACP-CHI 20 ZONE	ND	2	4	3
	1 ZONE	ND	2	3	4
	ANIMALS SATS	ND	2	4	3
	CFS	ND	2 *	4	3 *
	ANALYTICAL CHAS	ND	2	4	3
2.2 BTU PER FT ² SEC	FACP-CHI 20 ZONE	ND	ND	ND	ND
	1 ZONE	ND	2	3	4
	ANIMALS SATS	ND	2	4	3
	CFS	ND	3 *	4	2 *
	ANALYTICAL CHAS	ND	2	4	3

* = BASED ON LIMITED DATA

ND = NOT DETERMINED, TESTED ONLY AT ONE HEAT FLUX

1,2,3,4 = ASSIGNED RANKING, LEAST TO MOST HAZARDOUS

HAZARD ANALYSIS

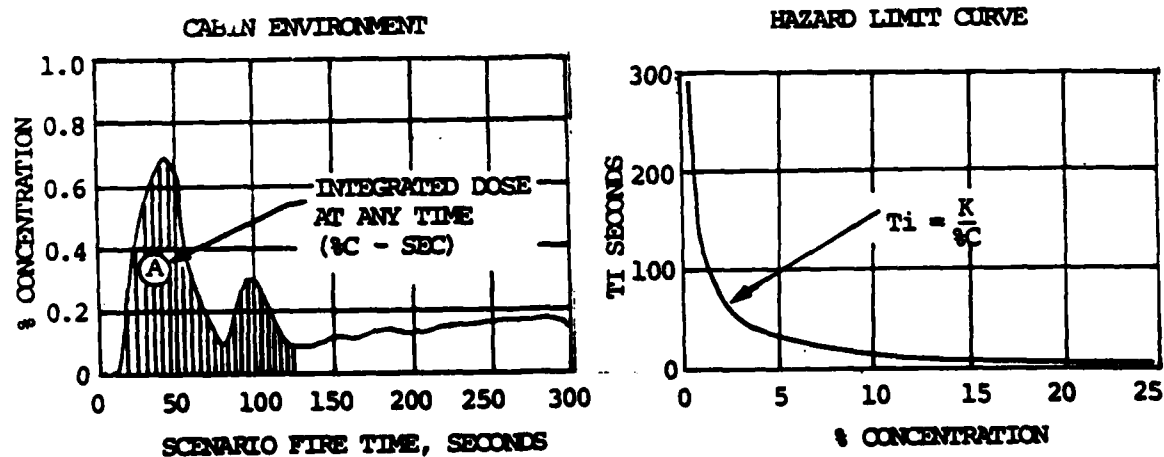
The thermal tolerance curve was taken from Crane's regression analysis of data of human collapse from thermal overload. The fractional effective thermal dose (FD_T) is the ratio of the integrated cabin temperature at any scenario fire time to the amount of heat the body can absorb before collapse. As was the case for the remaining hazards, the empirical data used to derive the tolerance curve was limited to use over the crash fire scenario time (5 minutes).

It was assumed that gases in the combustion mixture had no known synergistic (greater than additive), or antagonistic (mutually subtractive or cancelling) toxic effects. A further assumption was made that the short-term incapacitation concentration-time relationship for systemic toxic gases (CO, HCN, etc.) also applied for irritant gases (HCl, HF, etc.). The final general relationship for each of the toxic gases had the following form:

$$T_i = \frac{K}{C}$$

Where: T_i = Time to incapacitation (seconds)
 K = Incapacitating dose (a constant different for each gas)
 C = Concentration of gas (%)

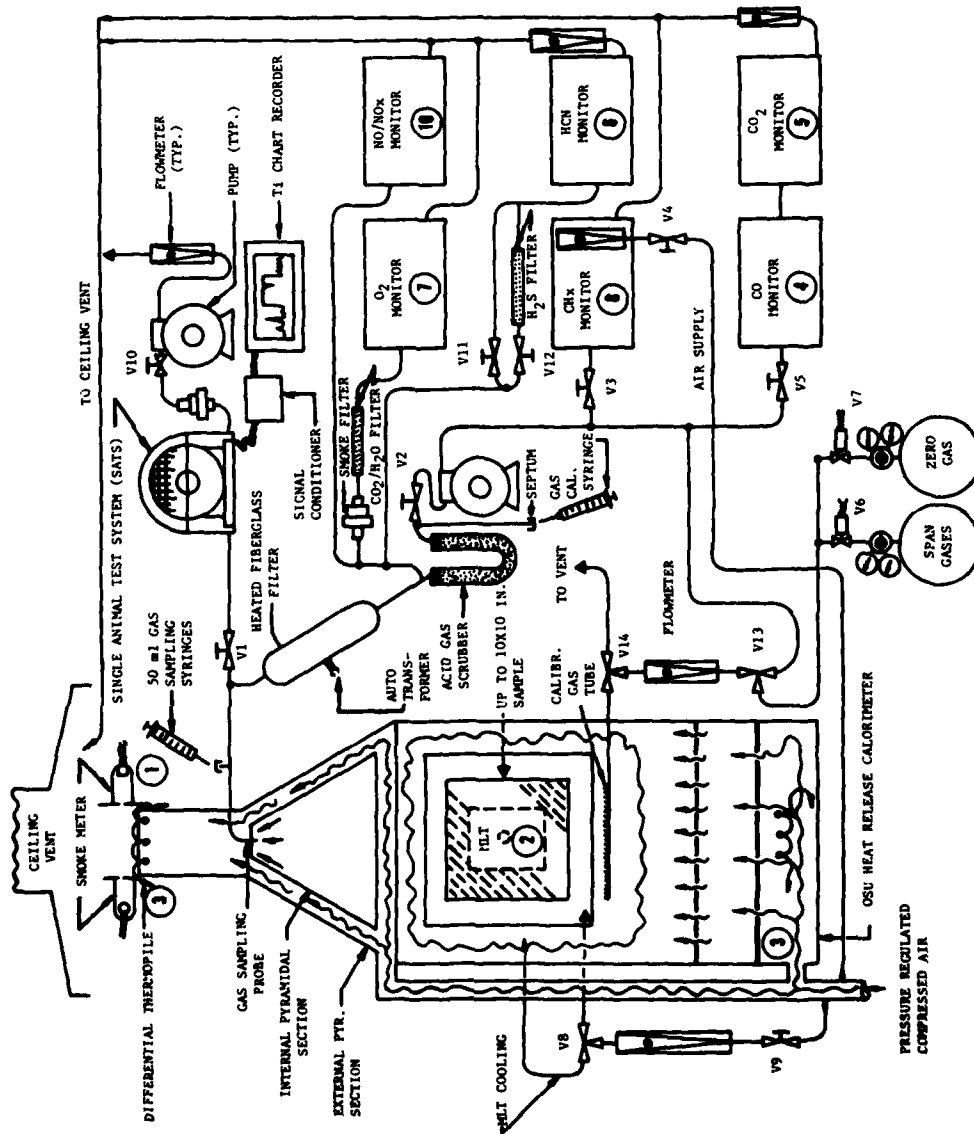
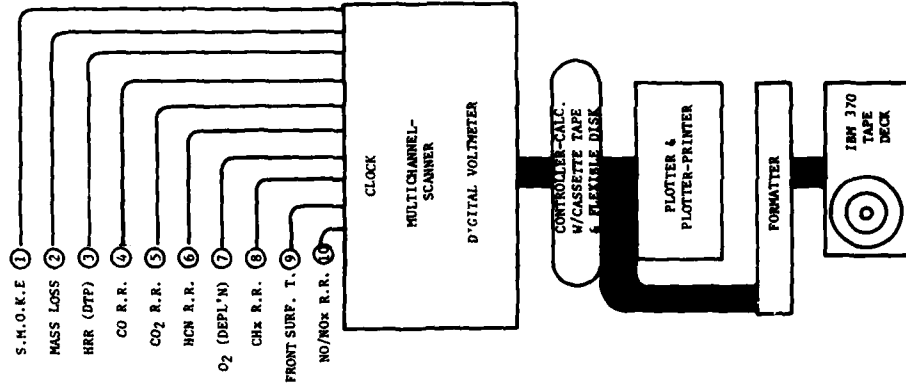
The fractional "effective toxic" dose (FD_G) is the ratio of the area, A , under the cabin concentration-time curve to the incapacitating dose, K , for each gas.



$$FD_G = \frac{A}{K}$$

SCHEMATIC DIAGRAM OF THE CHAS/SATS

HP AUTOMATIC DATA ACQ. SYSTEM



CONCLUSIONS

1. The Combined Hazards Analysis System (CHAS) test methodology developed during this study provides extensive and repeatable information related to heat, smoke and toxic gases hazards of a single aircraft material under a possible range of controlled test conditions encountered in a post-crash fire.
2. The equipment and instrumentation needed to assemble the CHAS are commercially available. This apparatus appears useful for the development of new fire resistant cabin material systems. The CHAS concept allows assessment of not only the flammability of material systems, but as well, the interaction of smoke and toxic gases.
3. CHAS test costs (labor) exceeded currently used FAR 25.853 flammability and NBS smoke chamber materials test costs by a factor of two or three, depending on the number of gases assayed.
4. The concept of transforming all CHAS hazard measurements to a common denominator-escape time-by application of fire and human survival models provides a method of combining and weighing the relative importance of the various hazards.
5. The Combined Hazard Index (CHI) of a material proposed by this study is the calculated escape time for the test conditions used. The validity of the CHI calculation is dependent upon the validity of the CHAS test methodology, human survival model and mathematical fire model.
6. It was beyond the scope of this study to establish the relationship between the derived human survival model and true escape potential of humans in a fire environment. However, it should be recognized that the survival model used is a simplified model since it contains (1) estimated 5-minute survival limits, (2) assumed hyperbolic relationship between concentration and escape time for each toxic gas hazard, (3) an unrealistic treatment of the dangers of smoke obscuration, and (4) an assumption that all hazards are additive.
7. The fire model developed in this study is a simplified semi-empirical model. The agreement between fire model predictions and large-scale test measurements was found to be reasonable for temperature and smoke but lacking for toxic gases.

I. INTRODUCTION

PURPOSE

The purpose of this program is to devise and evaluate a laboratory scale method for testing and ranking an aircraft cabin material for its collective combustion hazards under test conditions relating to a post-crash cabin fire. To achieve this objective, a multidisciplinary technical approach was required to develop the concept and the methodology which included the following elements: (1) multiple instrumentation, specific for the detection and quantitative measurement of fire hazards evolved as a material burns, integrated into one laboratory test system designated CHAS (Combined Hazards Analysis System); (2) a fire analysis computer program that calculates, from CHAS data, the quantities of heat, smoke, and toxic gases in twenty zones in a selected aircraft cabin or in a single zone cabin section; (3) input of preselected human hazard limit data needed for the computer prediction of occupant remaining escape time for each hazard, and for the combined measured hazards; and (4) a set of large scale burn tests to demonstrate the correlation of the laboratory predicted hazards (relating to occupant escape times) with those measured in the large scale tests. The methodology is limited to evaluating hazards generated by a single material subjected to thermal environments simulating a low-impact crash-survivable fire scenario.

This approach, which determines occupant escape time as a common denominator for the critical hazards encountered in cabin fires, is called the Combined Hazard Index (CHI).

BACKGROUND

During 1974-1975 the FAA published notices of proposed rule making relating to smoke and toxic gas emissions from aircraft cabin materials (References 1 and 2). As a result of responses to these proposals it was recognized that flammability, smoke and toxicity must be considered simultaneously in rating a material and that this technology did not exist. It was also desired that the rating be related in some manner to response of the material in an actual cabin fire. A material must be rated by laboratory testing and the state-of-the-art was such that a number of tests were used to measure only a few unrelated combustion characteristics of a material.

Conventional "standardized" tests, i.e., for flame spread; FAR 25.853 burn test, limiting oxygen index (LOI), and ASTM E-84 tunnel test; for smoke, NBS and XP-2 chamber tests; and for flash and auto ignition temperature, ASTM D-1029 and NBS flash fire cell, do not individually nor in combination meet the requirements and objectives of the CHI development program. Each of these tests are designed to measure one or two fire response characteristics for a material, holding certain recognized independent variables constant, to attain a certain degree of reproducibility in measuring the desired characteristics. The difficulties in using a "battery" of such test methods is that a large quantity of data results, relating material response to specific heat sources. Instead, data relating directly to personnel survival is needed. Toxicity, for example, is not an inherent property of a material. A summation of the flammability, toxicity and smoke (visibility) hazards as decomposition products in a closed environment; however, do relate to survival.

The following is the original work statement for the CHI program which was initiated in September of 1977:

1. Develop a combined hazard index time scaled against a specific post-crash fire environment covering an assumed maximum emergency evacuation period of five minutes. When a specific combustion hazard becomes critical within the five minute limit, it is identified and accounted for in the combined hazard ranking. A cabin fire environment will be simulated by full-scale tests representative of an actual post-crash accident scenario and fire.
2. Establish the limiting hazards of the combustion products of a material based on physiological limits of humans; i.e., time-to-incapacitation resulting from effects of heat, smoke, gases, etc., on cabin occupants attempting to evacuate the cabin under post-crash fire emergency conditions.
3. Account for the following combustion properties of materials in development of the Combined Hazard Index method:
 - a. Ease of ignition and melting and dripping characteristics.
 - b. Flame spread reate; horizontal and vertical.
 - c. Smoke emissions rate; flaming and smoldering.
 - d. Smoke density; flaming and smoldering.
 - e. Toxic gas emissions and rates for carbon monoxide, hydrogen cyanide, hydrogen chloride. The methodology will be capable of integrating hydrogen sulphide, hydrogen fluoride, hydrogen bromide, sulphur dioxide, formalydehyde and other gases consistent with state-of-art.
 - f. Heat of combustion
 - g. Flash-fire propensity.
 - h. Lachrymal affect of gaseous combustion products on visibility.
4. Utilizing cabin fire modeling technology, consider the effect of the magnitude and propagation rate of heat, temperature, smoke, gases, etc. as generated by a materials fire in one portion of the cabin, on adjacent and distant cabin environments and materials as could occur during the aforementioned emergency evacuation process, in developing the Combined Hazard Index methodology.
5. Select wide-body type transport cabin materials to develop, demonstrate and validate the Combined Hazard Index; e.g., ceilings, sidewalls, passenger service units, seat upholstery/cushions, and other large areas/large quantity materials which significantly contribute to a cabin fire. (Four wall and ceiling panels representing old and new constructions were selected.)
6. Use existing test equipment and standards wherever possible. (New test equipment and modifications were minimal and are described in a Part II report.)
7. Evaluate the economics of the final Combined Hazard Index methodology during this development to assure that the final method will be

cost-effective when utilized by industry to evaluate materials for production applications and conditions; i.e., the methodology shall utilize laboratory test results, cabin fire math modeling, physiological hazard limits and analytical techniques to rank a material.

8. Base combustion properties of materials such as heat of combustion, flame propagation, flammability, smoke density, toxicity and flash-fire propensity, on existing or proposed Federal Air Regulations or other recognized standard tests and the final methodology must be capable of accurately accommodating improved criteria when it becomes available.

Originally the program consisted of three phases scheduled for completion over a period of twenty-five months. Phase 1 was a planning phase detailing the concept and the technical approach for developing and validating the CHI methodology. Phase 2 was the development phase devoted to experimental laboratory testing of a typical large area cabin material to develop and finalize the CHI methodology. Phase 3 was the demonstration and correlation phase which included CHI Laboratory and full scale testing of three additional large area materials, different in composition than the Phase 2 material. The purpose of these tests was to demonstrate that the hazards predicted by the computer program from the CHI laboratory tests agreed with those measured during large-scale burn tests to a reasonable degree. In accordance with review decisions at the end of Phase 1, the first phase 2 plan was modified to incorporate large-scale testing of the first cabin material along with the laboratory method development effort. This was necessary to develop the technical linkage between the laboratory test data and the fire analysis computer program for the purpose of improving the predictive capabilities of the computer program.

A review of the Phase 2 (modified) program results revealed that further effort was required to develop the predictive capabilities of the CHI methodology. Therefore, the program was further modified to increase the experimental data base for use in development using the three additional cabin materials originally reserved for testing in Phase 3.

Four panel constructions were tested during the program. The first panel was a current wide-body modified phenolic construction with decorative facing on both sides as used for galley and lavatory walls. This panel was only tested in the CHAS/SATS (SATS = Single Animal Test System) and in the cabin fire simulator (CFS) at one heat flux during the earlier Phase 2 effort. The second was an acoustical, perforated ceiling panel of current construction. The third was a pre-1976 design using wood veneer facing and "self extinguishing" paper honeycomb core. The fourth panel was similar in construction to Panel No. 1, except that epoxy instead of phenolic was used in fabrication.

The original Phase 3 demonstration was combined with the new Phase 2 effort in the final contract revision, to test three large-area aircraft panels of differing chemical composition at three different heat flux levels consistent with those measured near centerline locations in full-scale cabin fire tests. The materials (panels) were tested at these flux levels in the integrated CHAS laboratory equipment, and in a full size cabin fire simulator to be described later. Two of the three materials were used to complete the fire analysis

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II. CHI METHODOLOGY DEVELOPMENT CONCEPT

BASIC CONCEPTS

The unique feature of the CHI approach was the selection of a common denominator for flammability, smoke (visibility) and toxicity. This common denominator is escape time based on personnel hazards in the cabin environment produced by the material being rated. Measuring hazard levels is in contrast to measuring material behavior (burn length, flaming time, etc.) as was formerly done.

Escape time requires not only hazard rate measurements but establishing personnel hazard limits. A maximum end point dose (concentration x time) for each hazard and consequently an indication of survivability in an environment below that limiting dose, was established as criteria for material rating.

The hazard limit end point for gases was that dose at which a passenger's ability to escape would not be physically impaired. The hazard concentrations used in determining these doses are not numerically equivalent to the standard threshold limit values (TLV) used for industrial exposures. The end point dose, in addition, has been adjusted to minimize the probability for post-escape mortality or lasting harmful effects. Lacrimation was also considered during the study phase of the program as a possible endpoint. Irritant gases cause lacrimation at lower concentration levels; however, there is no practical way to measure the combined combustion products lacrimation levels by instrumental methods. Such an endpoint was also judged to be too stringent for use in materials evaluation, and therefore was not included in the final methodology.

"SMOKE" as used in this program refers only to visibility as measured by the NBS Smoke Chamber or the CHAS. Thus it is not a hazard in the same sense as a gas or temperature but only slows escape and increases exposure to other hazards.

A laboratory method for measuring these hazards from a single test (of replicates) plotted against time was then required. The heat release rate calorimeter developed by E. E. Smith at Ohio State University was selected and modified to provide the capability of measuring gas hazards in addition to heat and smoke emissions. The basic size and operational characteristics of the apparatus were preserved. Only relatively simple modifications were required to permit monitoring the gas emissions and assessing the toxic response of a test animal to the combustion products generated.

Escape time was calculated using a suitable computer program relating to a cabin of specific size and to a real fire situation. The computer program predicts cabin hazard levels versus fire scenario time from the CHAS materials test data. The CHI (escape time) is, in turn, calculated from the human tolerance limits to the hazards in this environment. The computer program has two versions. One divides the cabin into twenty zones while the other is a single zone model. The single zone may be considered as a section through the cabin with a well mixed atmosphere. The methodology developed permits many variations without changing the basic concept e.g., changing the fire scenario, changing the cabin size in which the fire occurs or improving human hazard limits when such advanced criteria become available.

Verification of the computer program was accomplished by predicting the cabin environment in a full size simulator. This Cabin Fire Simulator (CFS) is 40 ft. long and 12 ft. in diameter (Figure 1). A radiant heat source and propane pilot flames were used as a "clean" source to ignite the 4 X 6 ft. panels. Air flow through the simulator was controlled and variable.

Burn test data measured by the instrumentation placed in the CFS were recorded and processed by a computer.

The major steps in determining the CHI of a material are shown in the flow chart (Figure 2). These steps and other factors will be explained in detail in later paragraphs.

CRASH FIRE SCENARIO SELECTION

For the purpose of developing the CHI methodology it was necessary to select a survivable crash fire scenario of sufficient severity to produce hazardous levels of heat, smoke, and toxic gases within a 5-minute limit (assumed maximum emergency evacuation time).

The scenario selected was a real accident that occurred in London in 1968 (References 3 and 4). All elements necessary for a rapidly developing post-crash cabin environment which would affect passenger survival within that time frame were present. The cabin in this scenario was breached and partially enveloped in a jet fuel pool fire with exit doors open; however, sufficient detail was not reported so that it was necessary to postulate specific values caused by ingress of fire, radiant heat and cabin ventilation induced by a prevailing wind.

A number of full-scale and simulated fuselage post-crash type fire tests have been conducted to determine the heat flux levels measured both at the outer cabin skin and on various interior surfaces inside the cabin (References 5 & 6) in quiescent atmospheres and under the influence of wind.

Based on the scenario and full scale test data, the CHI program materials were tested at 2.2, 3.08, and 4.41 Btu/ft² sec (2.5, 3.08, and 5.0 W/cm²) heat flux in the CHAS and CFS. These flux levels were selected to compare the materials response in laboratory and full scale over a range of thermal exposures expected to exist in a survivable cabin environment. Air flow was standardized at 875 ft³/min to minimize testing and as a reasonable flow rate that relates to a survivable crash with cabin doors open. Airflow in the CHAS tests was standardized at 60 ft³/min.

LABORATORY METHODS

As a part of the 1975 Douglas Aircraft Fire Safety Program the Ohio State University (OSU) Heat Release Rate (HRR) Calorimeter was selected for modification and developed to test materials for their combined hazards emissions. This calorimeter basically produces analog electrical signals that are readily calibrated to determine the quantities of smoke and heat produced in real time in a burn test. In order to expand the OSU hazards measurement capabilities a gas sampling train and associated gas monitoring instrumentation were intergrated with it. Reference 7 describes the OSU calorimeter and outlines the test procedures for its use.

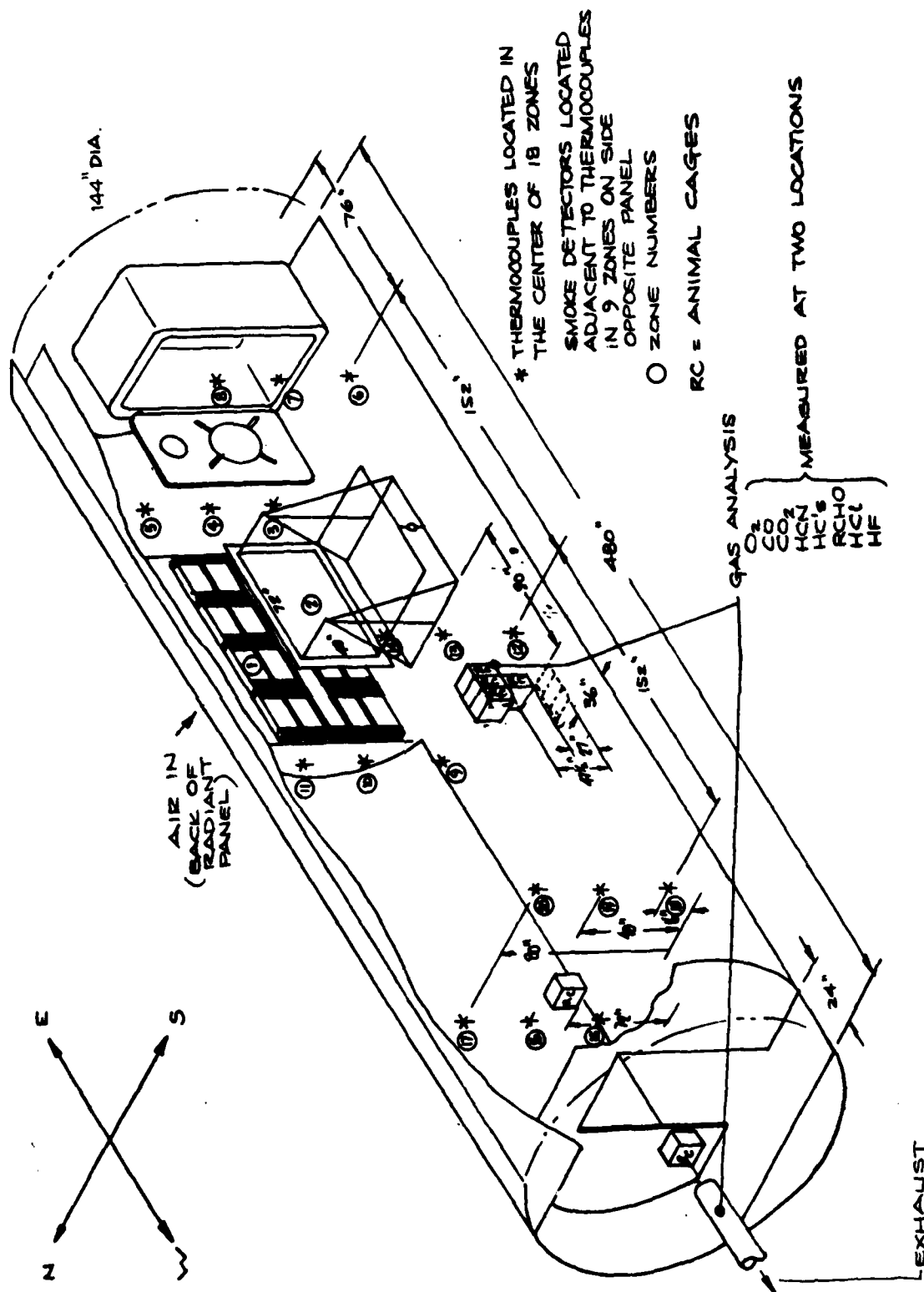


FIGURE 1. CHI TEST SETUP IN CFS

MATERIAL BURNS IN CHAS

HAZARDS RELEASE RATE (SMOKE, HEAT & TOXIC GASES) MEASURED OVER 10
MINUTE BURN TIME

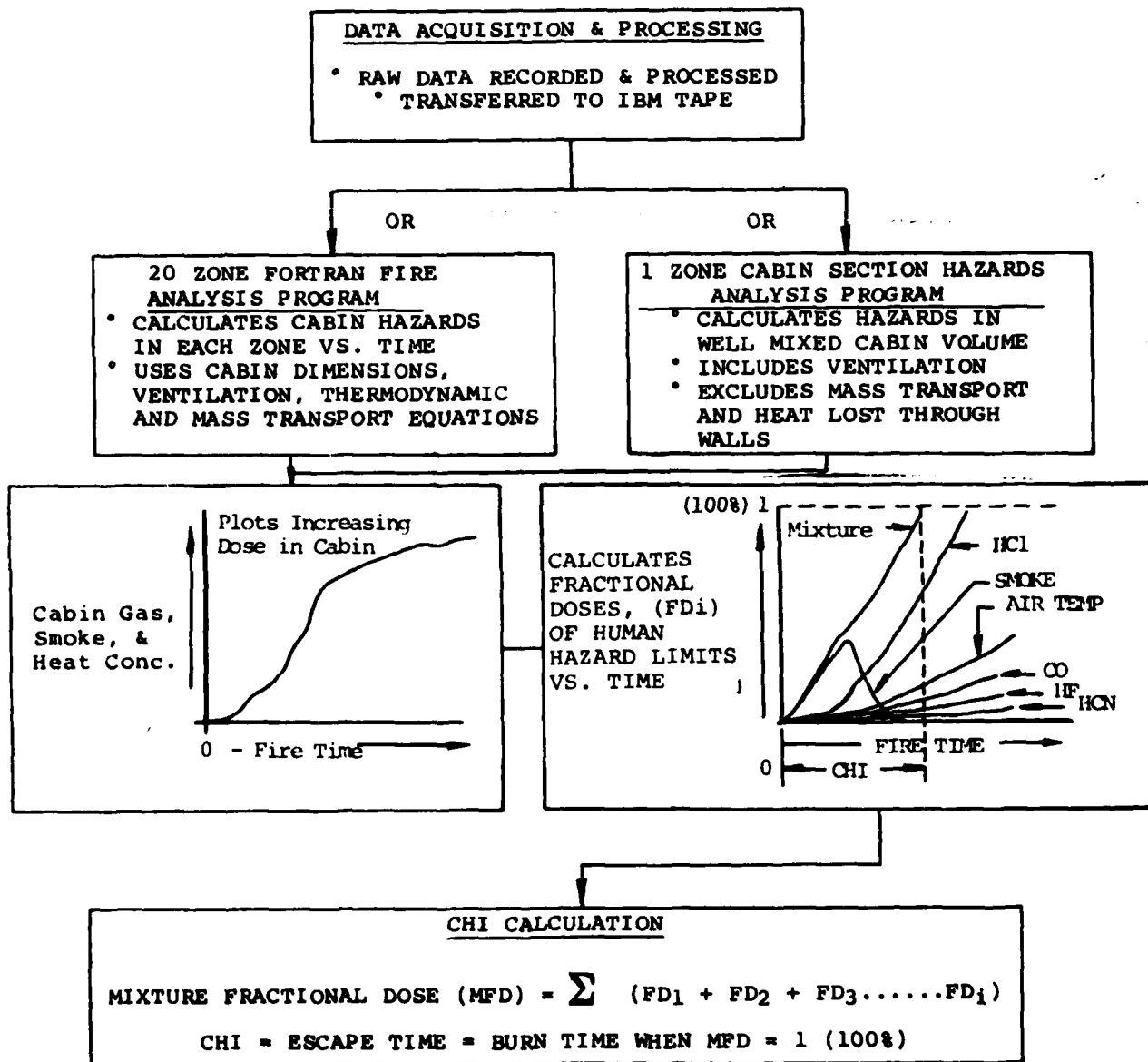


FIGURE 2. FLOW DIAGRAM SHOWING STEPS FOR DETERMINE CHI FOR A MATERIAL

The gas monitoring instruments were selected against the following criteria:

- (1) specific response to the gas specie being measured,
- (2) detection sensitivity and dynamic range,
- (3) electrical signal readout stability and freedom from drift,
- (4) speed of response to an incremental change in combustion product concentration, and
- (5) ease of calibration.

A sampling system also had to be provided for spot checking the release rates of those toxic gases for which continuous monitoring equipment was not available.

A new low thermal capacitance sample holder was designed and built to accommodate larger sample sizes. This holder was designed to allow free access of air to the thermally unexposed back surface of a test specimen (panel material). While the NBS smoke chamber and OSU HRR test procedures call for backing up the specimen with a non-flammable insulating board, all of the burn tests were conducted without this board. This procedure was adopted because materials can catch fire on the backside by burnthrough. Also, partition panels and ceiling panels mounted in aircraft have free access to air on both sides, and often have different materials of construction on the backside. A Single Animal Test System (SATS) consisting of a test chamber for exposing rats to the combustion products, connected in parallel with the gas monitoring system, and a sample mass loss transducer to measure mass burning rate, completed the automatic monitoring instrumentation combined directly with the calorimeter. This equipment assembly is referred to as CHAS/SATS. (Figure 3).

The last important modification was dictated by the criteria that the method should be able to acquire and process the data obtained from a test in minimum time. This would optimize cost-effectiveness by reducing the turn-around time for repeat testing. To satisfy the program objectives, this data handling system had to be compatible with and be able to record the data in a form that could be input directly into a Fortran IV Fire Analysis Computer Program (FACP). The CHI computations are the final product. The computer program concept will be discussed in a following subsection.

The gases contributing the toxic threats in aircraft cabin material fires, included in the program, were carbon monoxide (CO), hydrogen cyanide (HCN), nitrogen oxides (NO_x), hydrogen chloride (HCl), hydrogen fluoride (HF), total aldehydes (as formaldehyde, RCHO), carbon dioxide (CO₂), and oxygen (O₂) depletion. Hydrogen bromide (HBr) was also important since it is very irritating to the lungs, eyes and skin. Hydrogen sulfide (H₂S) is a systemic poison similar in toxicity to HCN, but different in mode of action. H₂S was not produced in significant quantities by any of the four panels employed in the CHI program. However, it has been included in the methodology. Other gas combustion products originally included in the program, i.e., ammonia (NH₃) sulfur dioxide (SO₂), carbonyl chloride (COCl₂) can not be monitored in real time and require time interval "batch" sampling and post test analysis by microchemical techniques. Only traces of COCl₂ are found in the combustion products of chlorine containing polymers. NH₃ and SO₂ are most commonly found in the combustion products of wool.

The procedures used in CHAS/SATS testing of materials required that certain optional independent test variables be fixed to aid in developing the CHI



FIGURE 3. THE COMBINED HAZARDS ANALYSIS/SINGLE ANIMAL TEST SYSTEMS-CHAS/SATS

methodology concepts. Thus, the total airflow rate for all runs in the CHAS were set at 60 ft³/min. This was adopted to minimize the dilution of combustion products (heat, smoke, and gases) evolved by the test sample. Twenty-five percent of the total airflow (15 ft³/min) flows over the sample and dilutes the emitted products. This flow rate was necessary also to produce gas mixture concentrations introduced into the SATS toxic enough to obtain an animal response in the short burn times (10-minutes). Animals (rats) were used in the laboratory tests (CHAS/SATS) as well as in the large-scale CFS tests to correlate animal toxicity response with analytical gas release data. Since animals are, in effect, integrating sensors giving a biological response resulting from exposures to the combined combustion hazards, their use gave additional confidence in the CHI methodology. Although desirable for this research program, it is not expected that a materials evaluation test would include the use of animals in the test protocols for ranking materials.

The procedures used in CHAS/SATS testing of materials required that certain optional independent test variables be fixed to aid in developing the CHI methodology concepts. Thus, the total airflow rate for all runs in the CHAS were set at 60 ft³/min. This was adopted to minimize the dilution of combustion products (heat, smoke, and gases) evolved by the test sample. Twenty-five percent of the total airflow (15 ft³/min) flows over the sample and dilutes the emitted products. This flow rate was necessary also to produce gas mixture concentrations introduced into the SATS toxic enough to obtain an animal response in the short burn times (10-minutes). Animals (rats) were used in the laboratory tests (CHAS/SATS) as well as in the large-scale CFS tests to correlate animal toxicity response with analytical gas release data. Since animals are, in effect, integrating sensors giving a biological response resulting from exposures to the combined combustion hazards, their use gave additional confidence in the CHI methodology. Although desirable for this research program, it is not expected that a materials evaluation test would include the use of animals in the test protocols for ranking materials.

COMPUTER MODELING

The FORTRAN Fire Analysis Computer Program, FACP, implements the CHI concept by performing the following:

- (1) Translates CHAS burn data to any cabin size. As now written it uses the CHAS data to continuously calculate the CFS cabin environment from 0 up to 10 minutes burn time. The burn time is an input data number.
- (2) Calculates a human escape time resulting from exposure to toxic fire gases, elevated air temperature and smoke. As a hazard index, the escape time is standardized as the burn time at which the hazards mixture reaches a zero escape time.

The FACP used the data from CHAS tests to calculate the concentrations of each hazard varying with fire time in 20 zones within the CFS. The independent constants and variables required for these computations included the CFS volume (constant), the zone volumes (constant), ventilation rate (variable if desired), wall thermal losses, fire involved sample area (constant), and the flow dynamics constants. The CHI test setup is schematically illustrated in Figure 1. At the preselected location (zone 13) for a CHI measurement, each hazard level was continuously integrated over the burn time to calculate the

accumulating doses. As indicated in Figure 2, the dose of each hazard building up in CHI zone 13 is approaching an "effective dose" limit which prevents occupant escape from a cabin. Individual hazard exposure limit equations are used in the computer program to calculate the fire exposure times at which an "effective dose" is reached and escape is no longer possible.

In the FACP single zone model the entire volume of the CFS was treated as a well mixed environment. Calculations for the fractional dose variations in time increments over a 5 minute burn time for each hazard were summed to calculate a CHI.

III. EXPERIMENTAL APPROACH

LABORATORY EQUIPMENT AND METHODOLOGY

In the OSU calorimeter, a material is exposed to a preset radiant heat flux and preset airflow rate streaming upward over its surface. The material surface may also be subjected to a small gas pilot ignition flame, impinging on it or spaced above it in the airstream. Figure 4 shows a simplified isometric view of the basic OSU calorimeter chamber with the airflow distribution, radiant heat panel, pilot flame, sample injection side chamber, and vertical test sample. The basic HRR calorimeter is instrumented with a 6-junction (series connected), chromel-alumel thermocouple, differential thermopile (DTP). Three junctions of the DTP are located in the cold air entering the bottom of the chamber and the remaining 3 junctions are located at the top of the stack. This permits recording a dynamic differential temperature measurement as material burns in the chamber. As shown in Figure 4, a light attenuation photometer is located at the stack outlet to measure the rate of smoke evolution. In this simplified version developed by E. E. Smith, therefore, only smoke and heat release rates are calculated from recorded data.

To provide the capability of measuring the hazards required to develop the CHI concept, the basic OSU HRR Calorimeter was modified into the CHAS/SATS configuration (See Figure 3). This system is similar to an apparatus developed at the Dow Chemical Company by Herrington, et al (Reference 8). The principal unique modifications utilized in the CHI program include a mass loss transducer (MLT) integrated with a special low heat capacitance sample holder and injection mechanism (Figure 5), and the animal test. The sample holder was constructed from thin gauge stainless steel to avoid overloading the MLT unit. The holder thermal capacitance was low because of the low mass. Sample sizes up to 10 x 10 x 1 inch (25.4 x 25.4 x 2.54 cm) can be accommodated in the holder in a vertical orientation.

In accordance with the original CHI program work statement up to 15 gases were included in the methodology. In its present state of development CHAS monitors 6 of the 15 gases in real time. Real time, specific response, monitoring instruments were not commercially available for measuring the release rates of the remaining 9 gases. Since it was beyond the scope of the program to develop such instrumentation, "batch" sampling and post test laboratory chemical analysis techniques were used. These methods were selected from the scientific literature and modified, as needed, for use with the CHAS. In practice, an easily manipulated "batch" sampling technique was needed that would permit the operator to take replicate samples at accurately timed intervals. A release rate profile for each gas sampled was plotted and the values were used in the FACP as a contributing hazard for the calculation of a material CHI.

The paradigm used in the toxicity tests was based on the time of useful function originally developed by Gaume (Reference 9). This response was measured in terms of the time-to-incapacitation (Ti). The Ti is determined as the number of seconds of elapsed time from injection of the sample into the CHAS to the time (sec) of collapse of the test subject. An electrical signal/contact bar sensor detected the collapse of this test subject. In compliance with the FAA's desire to utilize animal Ti as a measure of the toxicological hazard of the combustion products, for comparison with CHAS and CFS gas concentrations, Douglas designed and fabricated two exposure chambers

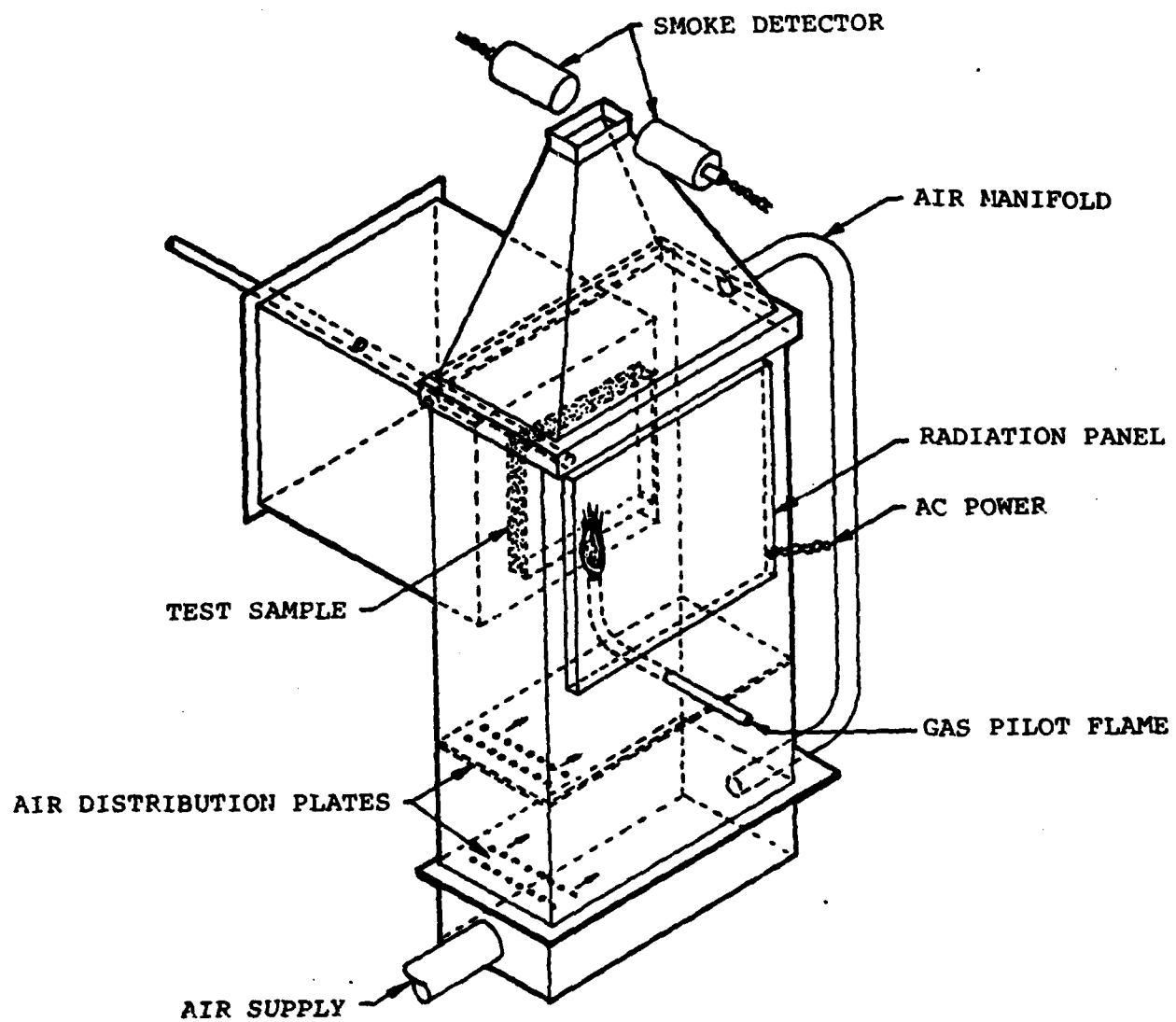


FIGURE 4. OHIO STATE UNIVERSITY HEAT RELEASE RATE CALORIMETER



FIGURE 5. SAMPLE HOLDERS AND INJECTION MECHANISM (WITH MLT UNIT)

of different sizes and internal volumes. The larger version, or multiple animal test system (MATS) (discussed later under CFS Testing), exposed 3 rats within the same chamber. As shown in Figure 6, the single wheel version, called SATS, was integrated with the CHAS to obtain Ti data along with the other monitored release rate data. The single wheel version, having a smaller free volume, requires a shorter time to replace the atmosphere in the animal chamber with the combustion products extracted at a constant pumping rate from the gas sampling probe at the top of the inner pyramidal section in the HRR calorimeter. Because of the dilution occurring in the HRR chamber, toxic dose buildup in the animal chamber must be attained rapidly and retained to obtain a Ti or Td (time to death) result in less than 20 minutes. The developed test procedure, therefore, provided for a gas and smoke pumping rate of 14 liters/min through the chamber which has a free volume of 5.4 liters. This sampling rate therefore allows 2.59 nominal volume exchanges per minute. During a test, flow into SATS was stopped when CO reached peak concentrations to prevent dilution thereafter at decreasing sample CO emission rates.

The CHAS data output from the DTP, smoke photometer, and continuous combustion gas products monitors was recorded and processed by a 10 channel Hewlett Packard 3052A Automatic Data Acquisition System (ADAS) interfaced through a general purpose interface bus (GPIB) with a HP9825B computer controller (65K bytes of random access memory), a 9862A plotter, a 7245A plotter printer and an auxillary 9885M floppy disk memory (400K bytes memory).

Software programs were written to process the data in real-time over burn periods extending to 30 minutes (if required). The scanner in the ADAS takes data, once per second for each of 10 channels, into disk memory for post test processing and plotting of release rate curves. The program also calculates the peak release rates and the total (integrated) hazards accumulating in selected time intervals, normalized by sample area.

Six thousand data points were recorded by this system for each 10 minute burn test in the CHAS. In order to utilize this data in the FACP an additional Dylon Model 1015A GIPB buffered controller-formatter was interfaced with the CHAS ADAS. These data were transferred to a 7 inch IBM Computer Tape, and used as input to the FACP. The input CHAS data and the output of the FACP were printed out by the IBM 370 computer which became a record of the input/output of a material test. Figure 7 shows the CHAS ADAS System.

The operational characteristics of the temperature, smoke, and continuous combustion gas monitors is summarized in Table 1. A complete list of CHAS equipment is to be found in the Part II Report, Appendix A. A detailed description of the modifications to the OSU HRR Calorimeter needed to convert this equipment into CHAS/SATS, dimensional drawings or schematics of the important modifications, test procedures, instrument calibrations and a listing of HP-ADAS programs and data reduction also can be found in the various sections of Part II.

CHAS/SATS TEST PROCEDURE - The CHAS/SATS is shown schematically in Figure 8. In this schematic, the relationship of the modified OSU HRR Calorimeter to the other major subsystems, i.e., the continuous gas monitors, SATS, calibration equipment, and the automatic data acquisition system is delineated. The basic test procedure (tentative ASTM Standard), described in Reference 7, has been

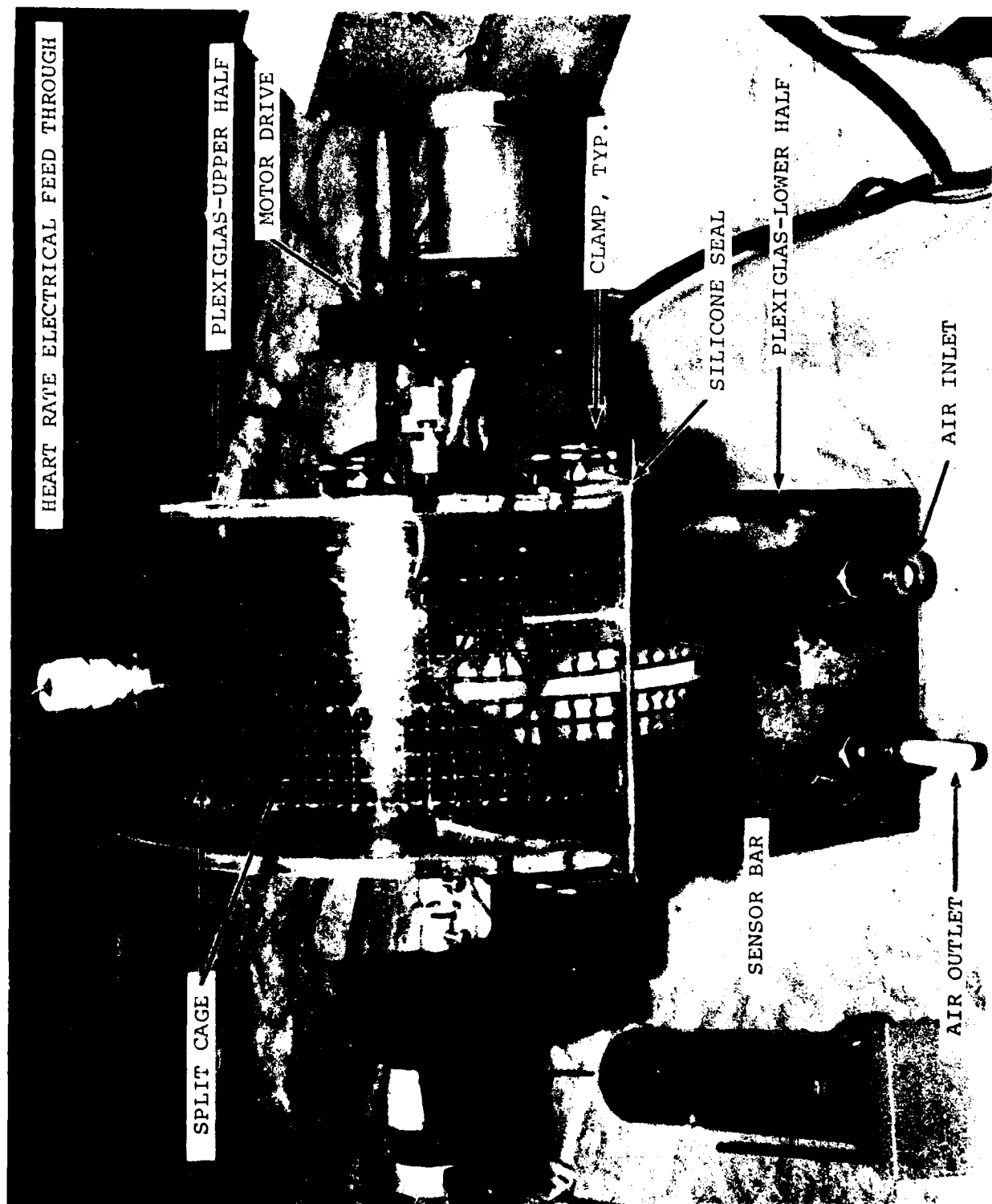


FIGURE 6. SINGLE ANIMAL TEST SYSTEM (SATS)

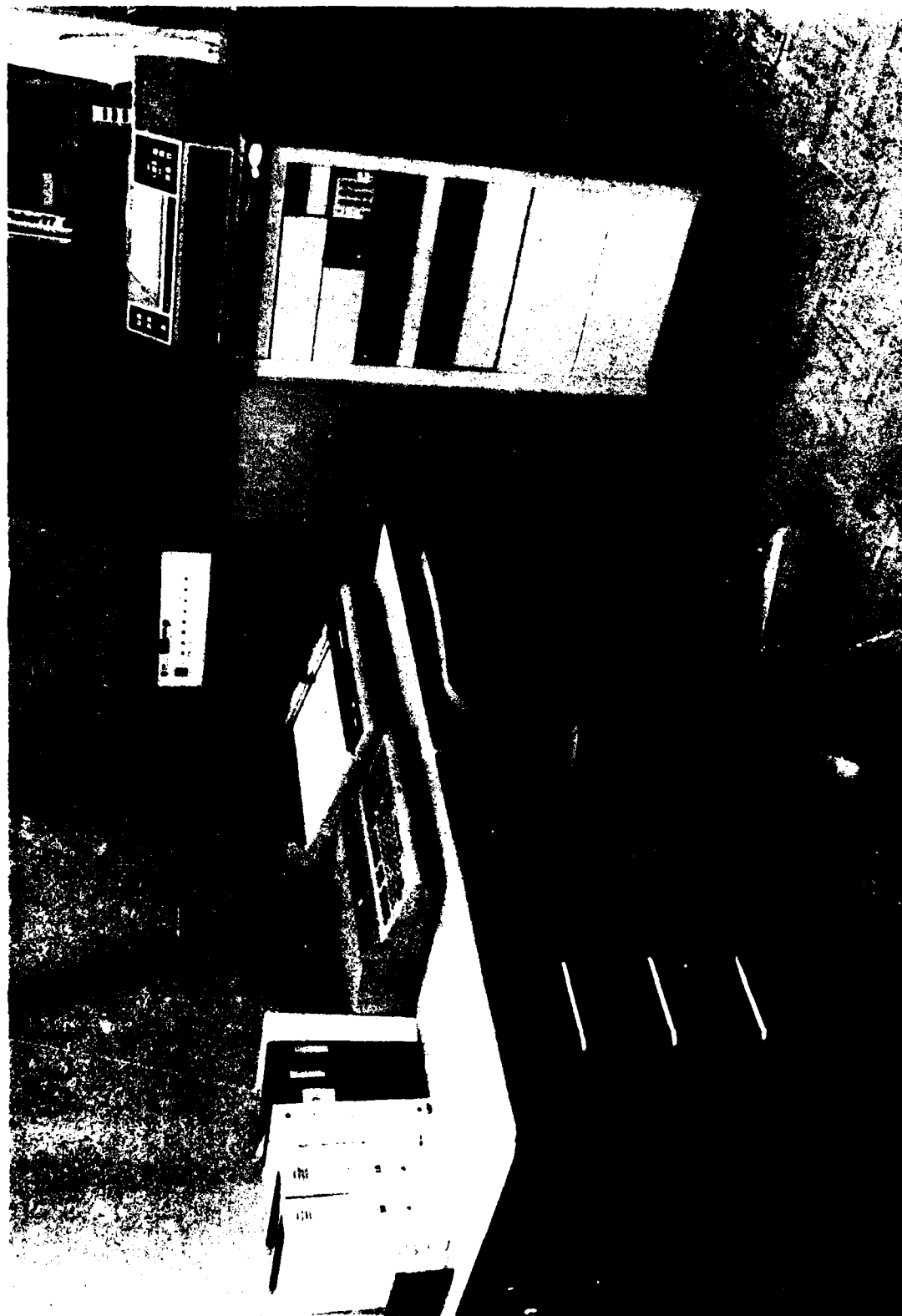


FIGURE 7. CHAS DATA ACQUISITION AND PROCESSING SYSTEM

TABLE 1
CHAS INSTRUMENTATION OPERATIONAL PARAMETERS

INSTRUMENT	HP 3052A ADAS CHANNEL NO.	RELEASE RATE PARAMETERS MEASURED	DETECTION SENSITIVITY & RANGE	TIME IN SEC TO RESPOND TO 90% OF PEAK	CHAS GAS TRAIN DELAY TIME-SEC	CALIBRATION METHOD
Smoke Photometer OSU Design	1	Smoke Rel. Rate Units SRR/m ² , min	1 - 400 ¹ 3 - 1090 ²	0.1	-	Standard Optical Density Filters
Mass Loss Transducer West Coast Res. Corp & Douglas Design	2	Weight Loss, g/min & Wt. Loss Rate, g/min, m ²	2 - 1000 g	0.01	-	Calibration Weights
Differential Thermo- pile, OSU Design	3	Heat Release, kW/m ²	2 - 1200 kW/m ²	Variable ³	-	Burning Gas of Known Heat of Combustion
Nondispersive Infrared Analyzer MSA LIRA 303	4	CO, ppm V/V	0 - 7500 ppm	2	17	Certified Cylinder Mixture
Nondispersive Infra- red Analyzer Beckman 864	5	CO ₂ , % V/V	0 - 3%	1	18	Certified Cylinder Mixture
Amperometric Analyzer Kintek (DOW)	6	HCN, ppm V/V	0 - 10,000 ppm	2-5	6	Dynamic Flow w/Permeation Tubes
Electrometric Analyzer Infrared Ind.	7	O ₂ , % V/V	0 - 25%	5	13	Air & Certified Cylinder Mixture
Combustible Gas Analyzer Teledyne 175A	8	CHx, CO, % V/V	0 - 5%	5-10	19	Certified Cylinder Mixture
Chromel-Alumel TC, Type K	9	Surface Temp., °K	0 - 1000°K	2-10	-	None
Chemiluminescent Gas Analyzer	10	NO & NOx, ppm V/V	0 - 10,000	2-12	15	Cylinder Mixture NO in N ₂ , Certified Analy sis

1 Range with Airflow Rate = 60 ft³/min; 10 x 10 Inch Sample Size

2 Range with Airflow Rate = 60 ft³/min; 6 x 6 Inch Sample Size

3 Time to Respond to 90% of a Heat Release Peak is Variable and is a Function of Intensity.

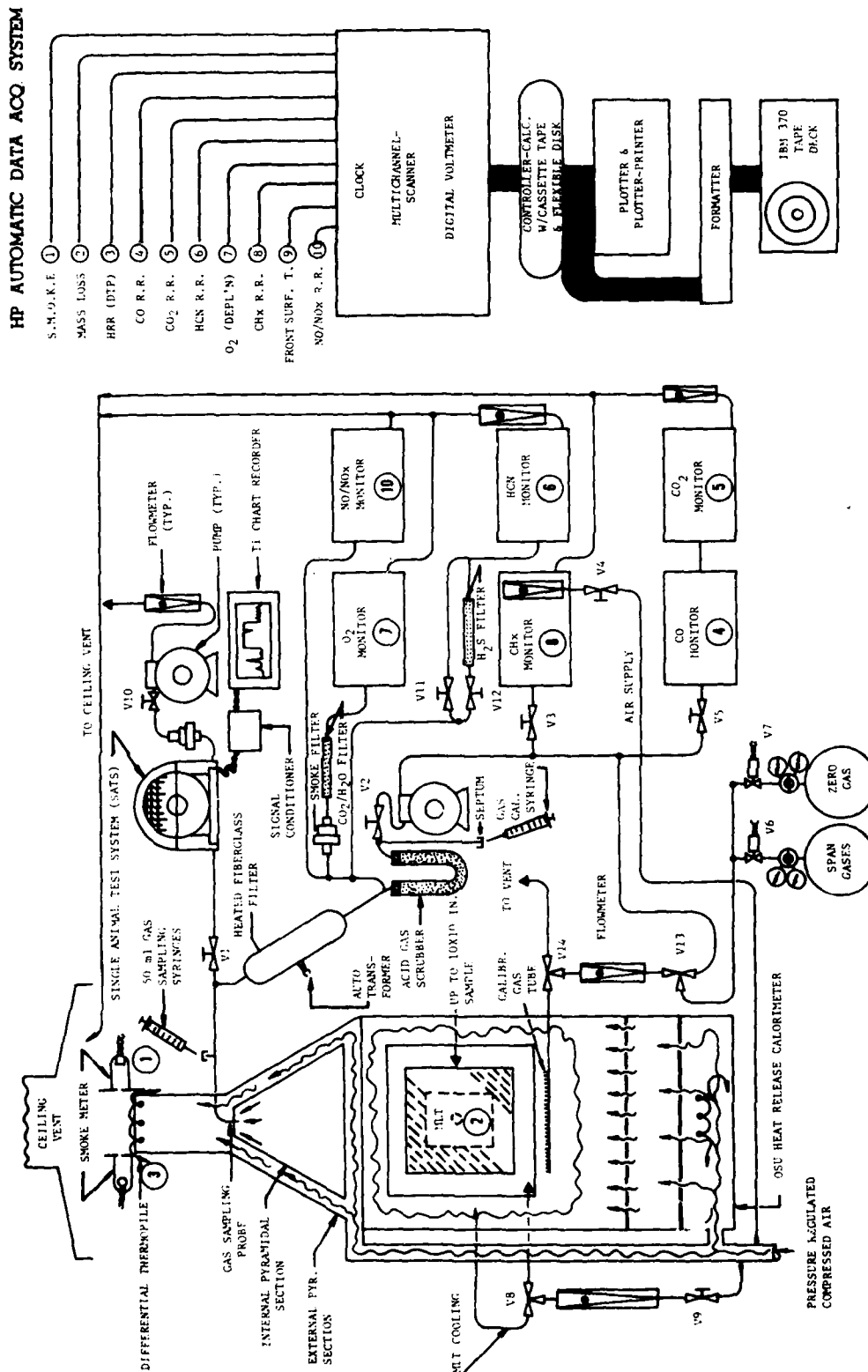


FIGURE 8. SCHEMATIC DIAGRAM OF THE CHAS/SATS

followed for the operation of the HRR Calorimeter and the preparation and introduction of the sample into the HRR inner burn chamber at the start of a test. However, additional steps were required to setup and complete a test run using the CHAS/SATS. The basic procedural steps for running a CHAS/SATS test are as follows:

- (1) The sample was cut to size (6 x 6 or 10 x 10 inch), weighed to + 0.1 gram (g) (weight recorded), and mounted in the sample holder (See Figure 5).
- (2) When thermal baseline was achieved after accurately adjusting the airflow rates and the selected radiant flux level (2.5, 3.5, or 5.0 W/cm²), the sample and operational parameters were keyed into the HP-ADAS program in preparation for a test run.
- (3) All gas monitoring equipment was calibrated (except HCN monitor, which was calibrated prior to testing) using zero and span gas mixture(s) of certified composition.
- (4) The SATS was prepared and checked out and the test animal (rat) was weighed in preparation for a test.
- (5) With systems checked and operating as confirmed by pretest initialization and readout of the HP-ADAS program baseline readings, the test animal was placed in the SATS and ventilation airflow established.
- (6) The sample holder/injection mechanism was introduced and sealed in position in the HRR hold chamber. Airflow was immediately established to cool the MLT, and the test animal cage rotation was started (6 RPM).
- (7) After 1.25 minutes to re-acquire the HRR thermal & gas monitor baselines, the HP-ADAS was activated to record all CHAS baselines (10 channels).
- (8) In rapid sequence, the sample was injected into the inner chamber of the HRR (and radiation doors were closed) and the HP-ADAS was started at this time (zero test time) along with the digital electronic timer needed to take the timed interval syringe "batch" samples during the test run (usually 10 minutes).
- (9) At the end of a test run, the sample was removed, allowed to cool down and the sample holder was loaded with the next sample. A new test animal and the SATS were prepared for the next test run.

DATA REDUCTION AND PROCESSING - After completion of the burn test, the 10 channels of analog data stored in the HP-ADAS floppy disk (or optionally on tape) as millivolt signals recorded at a speed of once per second were processed using the programs written to reduce the data and plot the hazards release rate curves.

The mathematical relationships and equations used to measure the hazards (heat, smoke, toxic gases) were based on the following:

$$(\text{Concentration of Hazard}) \times (\text{Airflow Rate}) = \text{Release Rate}$$

For heat release rate two methods were used during the CHI program:

- (1) Using the standard DTP:
Concentration = $C_p(T-T_0)$, Btu/lb
Airflow Rate = W/t , lb/min (for 60 ft³/min)
 $HRR = C_p(T-T_0) W/t$, Btu/min (1)

Where: C_p = specific heat of exit air, Btu/lb, °F
 $(T-T_0)$ = differential temperature (°F) of exit air (T) minus inlet air (T_0) at baseline (equilibrium) conditions as measured by the DTP

- (2) Using Oxygen Consumption Calorimetry (Reference 10): Because of the inherent time dependent response to rapid incremental changes in temperature produced by a burning material in the HRR, the DTP does not precisely match the heat release rate history. The DTP exhibits a first order lag in response, and the chamber walls absorb heat convectively and by radiation from the flaming test material. This heat slowly leaves the walls after the test, showing up as a temperature-time second order lag. The total measured heat can be almost completely recovered if the run extends for a time longer than 10 minutes. However, for optimum predictive purposes, the CHI FACP required input data free of the HRR system thermal inertia effects. Thus, the O₂ consumption method appeared to offer a straight-forward method for measuring heat release rate. It was found to be independent of the thermal inertia in the HRR chamber and the DTP. The method depends mainly on the mixing of the combustion gases, their transport time and the time constant of the O₂ gas monitor. Tests showed that the O₂ meter used in the CHAS tests on the last three panel materials detected a change in O₂ concentration in only a few seconds. Thus, a 90% response to a step function was recorded in 5-10 seconds, which indicated the suitability of the particular instrument for measuring the HRR.

The accuracy of the method also depends on the assumption that the heat release is constant for all polymeric materials consuming the same quantity of oxygen. This appears to be true for most materials to an accuracy of $\pm 5\%$ per Reference 10. The enthalpy value used in this program per unit of oxygen consumed was 489 Btu per cubic foot of O₂ consumed at normal temperature and pressure (72°F and 1 atmosphere). The average concentration of oxygen in the air flowing in the HRR chamber is 20.93% by volume. As the material burns, the oxygen is depleted in concentration.

$$\begin{aligned} \text{Depleted Concentration} &= (C_{air} - C_t), \% \text{ O}_2 \text{ by volume} \\ \text{Airflow Rate} &= V/t, \text{ cfm} \end{aligned}$$

Where: C_{air} = Concentration of O₂ in clean air, 20.93%
 C_t = Concentration of O₂ in depleted air at any time, %O₂ by volume.

$$\text{HRR} = (\text{C}_{\text{air}} - \text{C}_t) \times V/t \times 489, \text{ Btu/min} \quad (2)$$

For the other gases included in the CHAS method the release rate concentrations are converted to mass units, gram/minute:

$$\text{Gas Release Rate (GRR)} = (\text{Concentration of Gas}) (\text{airflow rate}) (C)$$

in which:

$$(\text{GRR}) = \frac{\text{ppm} \times \text{Liter} \times \text{gram}}{\text{min} \quad \text{liter ppm}}$$

C is a conversion factor having a different value for each gas. The exposed sample area (A) in square meters is factored in giving the following equation:

$$\frac{\text{GRR}}{A} = \frac{(\text{Concentration gas}) (\text{airflow rate}) (C)}{(A)} = \frac{\text{grams}}{\text{min, m}^2} \quad (3)$$

For smoke, the following equation was used (Reference 7) to calculate the quantity of smoke generated versus time in terms of units related to light transmission over a selected pathlength:

$$\text{Log}_{10} (1/T) \times L/A \times V_o/t \quad (4)$$

Where:

- SSU = Standard Smoke Unit
- T = Fraction of light transmission (0-1)
- Log₁₀ 1/T = Optical density (absorbance)
- L = Smoke detector light path length, m
- A = Sample area, m² (CHAS value)
- V_o/t = CHAS airflow rate (m³/min) leaving the HRR, 60 ft³/min (1.699 m³/min)

The gases not monitored in real time were sampled by extracting 45 ml of the combustion products over a period of 5 sec (approximately) at timed intervals during a burn test. Two sets of 10 syringes in each set were labeled to show the gas specie to be analyzed for in the combustion gas mixture and the time the sample was extracted. The syringe samples were taken alternatively from each set and sequentially within each set of syringes.

Each of the syringes in the first set were loaded with 5 ml of 0.05% MBTH solution (3-methyl-2-benzothiazoline hydrazone hydrochloride) to selectively absorb aliphatic aldehydes from the combustion gas sample. The syringes in the second set were loaded with 5 ml of 0.1 normal NaOH solution to absorb acid gases, i.e., HCl, HF, HBr from the combustion gas sample. The reagents were analytical grade purity and were prepared using distilled water.

Samples were taken through a silicone rubber septum mounted on a "T" fitting connected to the gas sampling probe line near the HRR upper pyramidal section (see Figure 8). Sampling sequences were started at 15 or 30 seconds (depending upon the sampling procedure selected) following injection of the sample into the HRR inner chamber (defined as time-zero). The 20 syringe samples were taken at the preselected timed intervals over the 10 minute burn test.

The absorbing solutions in each syringe were analyzed by the following standard microchemical techniques, References 11, 12, and 13:

HCl and HF (hydrolyzable Cl and F)	- electrometric titration with specific ion electrode
Aliphatic Aldehydes (as formaldehyde)	- Spectrophotometric (colorimetric) at 628 nm wavelength

The concentrations of each gas were calculated from the analytical data in terms of ppm present in the combustion gas stream averaged over the 5 second sampling interval during which it was taken. The data was entered into the HP-ADAS, processed, and plotted using a point connector program. This plot approximated the release rate profile for each gas specie expressed in terms of g/min, m² of sample. Additional data points were interpolated between each pair of experimentally determined data points using a conventional straight line computer program and transferred to the IBM 370 tape using the Dylon formatter interface.

The HP-ADAS analog data stored in memory on disc (or tape) for each hazard, and monitored automatically in real time, was processed using the above equations and individual computer programs written to process the data. Plots of the hazard release rates for O₂ (depletion), CO, CO₂, NO/NO_x, combustible gases (CH_x + CO), HCN, heat, and smoke together with those for HCl, HF, and aldehydes were generated for each test panel. The data, in digital form, (transferred to IBM 370 tape) was used in predicting the CFS test environment using the FACP.

The MLT data recorded from CHAS runs was used to compare the mass burning rates in CHAS with the same material burned in the CFS at the same average heat flux. This was of value in rationalizing differences in laboratory versus large scale behavior of each panel material.

MATERIALS

The specimens selected for testing in the CHI program included one type of current composite acoustical ceiling panel, two decoratively covered honeycomb panels used in partitions in wide-bodied commercial jet aircraft, and one decoratively covered wood-faced material used on older aircraft.

Table 2 lists the test panels and summarizes the data concerning their composition, size and weight as tested in the laboratory and in the CFS.

Five 4 X 8 ft panels were fabricated in one production batch for each construction. The processing was observed by an engineer to assure optimum reproducibility in materials of construction for the replicates of each type of panel.

Three panels of each construction were cut to 4 X 6 ft sizes for use in the CFS testing. The 2 foot ends cut from these panels were cut to the sizes required for CHAS/SATS testing. All samples were labeled in accordance with the coding shown in Table 2 so that the small samples were tested at the same heat flux levels in the CHAS/SATS as in the CFS.

Figure 9 shows the number codes identifying each of the three replicates cut to the required sizes in each construction. Traceability was monitored since the 4 X 6 ft section of each panel construction carried the same code numbers. Thus, panels 2-1, 3-1, and 4-1 were used only for testing in both the CFS and CHAS/SATS at 3.5 W/cm², and 2-3, 3-3, 4-3 panels were tested at 5 W/cm². In this test matrix the last -1, -2, -3 number identifies the replicate CHAS/SATS tests conducted on the smaller sections cut from the original panels. Evaluation of the preliminary results obtained from tests on Panel 2 indicated that the new O₂ monitor was sensitive to gas sampling stream pressure changes. This pressure effect caused small spikes to appear immediately following the extraction of each 45 ml syringe sample during the course of a run. Since these artifacts did not reflect true O₂ concentration changes, and resulted in an inflated HRR value, additional runs were made on each panel in which neither animals were used or syringe samples were taken. The data from these runs were composited with the data obtained on repeat runs which included the HCl, HF and aldehydes (syringe sampling) and recorded on the IBM 370 tape together with the other data used in the FACP calculations for CHI.

COMPUTER MODELING PROGRAM DEFINITION

The major goal of the CHI program was the development of a laboratory method useful for improving the fire safety of materials. It was beyond the scope of the investigation to develop a rigorous fire and human response model capable of predicting human survival time in actual fire scenarios because of the large number of variables. However, a hazards analysis approach, using a computer program relating fire hazards evolution rates with estimated human escape time potential for a specific fire scenario and material, was needed. This computer program had to provide sufficient accuracy to give some degree of confidence in the decision making process for selecting the most fire-safe materials. A cabin fire modeling program such as the Dayton Aircraft Fire (DACFIR) Computer Program was reviewed as too complex, and room fire programs under development by the, Harvard University, Notre Dame University or the National Bureau of Standards were designed for fire situations and scenarios different from those addressed in the CHI program.

TABLE 2
MATERIALS USED IN CHAS/SATS AND CFS TESTING

PANEL NUMBER TYPE AND CONSTRUCTION	PANEL SAMPLE CODE NO.	HEAT FLUX W/cm ²	CHAS/SATS		CFS	
			SIZE, IN	WT.	SIZE, IN	WT
#1 - PARTITION Phenolic fiberglass laminate/ phenolic-Nomex honeycomb core/ with PVF-PVC decorative film, both sides, W/Polyureth. & Epoxy Adh.	1	5.0	10 X 10 X .75 IN	275g 0.61 lb	48 X 72 X .75	21.3 lbs.
#2 - ACOUSTIC (PERFORATED) PVF/phenolic fiberglass / fly screen/epoxy adhesive/fiber- glass filled Nomex honeycomb/ phenolic fiberglass laminate	2-2 2-1 2-3	2.5 3.5 5.0	10 X 10 X 0.5 IN	156g 0.34 lb	48 X 72 X 0.5	11.9 lbs.
#3 - PARTITION PVC poplar wood/epoxy adh./FR paper honeycomb/epoxy/poplar wood/PVC	3-2 3-1 3-3	2.5 3.5 5.0	6 X 6 X 0.75 IN	147g 0.32 lb	48 X 72 X 0.75	31.1 lbs.
#4 - PARTITION Epoxy fiberglass laminate/epoxy adh./phenolic-Nomex honeycomb/ PVF-PVC decorative film, both sides	4-2 4-1 4-4	2.5 3.5 5.0	10 X 10 X 0.75 IN	270g 0.60 lb	48 X 72 X 0.75	20.9 lbs.

HEAT FLUX	DAC PANEL #2					DAC PANEL #3					DAC PANEL #4				
	2-2	2-1	2-3	2-4	2-5	3-2	3-1	3-3	3-4	3-5	4-2	4-1	4-3	4-4	4-5
2.5 W/cm ²	2-2-1 WO/Sx & G.S. 10680 10580	2-2-2 W/Sx & G.S. 13580	2-2-3 W/Sx & G.S. 13680	3-2-1 WO/Sx & G.S. 11580		3-2-2 W/Sx & G.S. 11680		3-2-3 W/Sx & G.S. 11780		4-2-1 WO/Sx & G.S. 12280	4-2-2 W/Sx & G.S. 12380		4-2-2 W/Sx & G.S. 12480		
				3-1-1 WO/Sx & G.S. 11480		3-1-2 W/Sx & G.S. 11280		3-1-3 W/Sx & G.S. 11380		4-1-1 WO/Sx & G.S. 12580	4-1-2 W/Sx & G.S. 12680 13380		4-1-3 W/Sx & G.S. 12780 13480		
				2-1-1 WO/Sx & G.S. 10280 13280		2-1-2 W/Sx & G.S. 10380		2-1-3 W/Sx & G.S. 10480		3-3-1 WO/Sx & G.S. 11880		3-3-2 W/Sx & G.S. 12080		3-3-3 W/Sx & G.S. 12180	
3.5 W/cm ²	2-3-1 WO/Sx & G.S. 13880		2-3-2 W/Sx & G.S. 13780		2-3-2 W/Sx & G.S. 10780 11080		3-3-1 WO/Sx & G.S. 13180		3-3-2 W/Sx & G.S. 12980		4-3-1 WO/Sx & G.S. 13080		4-3-2 W/Sx & G.S. 13080		
	2-3-1 WO/Sx & G.S. 13880		2-3-2 W/Sx & G.S. 13780		2-3-2 W/Sx & G.S. 10780 11080		3-3-1 WO/Sx & G.S. 13180		3-3-2 W/Sx & G.S. 12980		4-3-1 WO/Sx & G.S. 13080		4-3-2 W/Sx & G.S. 13080		
	2-3-1 WO/Sx & G.S. 13880		2-3-2 W/Sx & G.S. 13780		2-3-2 W/Sx & G.S. 10780 11080		3-3-1 WO/Sx & G.S. 13180		3-3-2 W/Sx & G.S. 12980		4-3-1 WO/Sx & G.S. 13080		4-3-2 W/Sx & G.S. 13080		
5.0 W/cm ²	2-3-1 WO/Sx & G.S. 13880		2-3-2 W/Sx & G.S. 13780		2-3-2 W/Sx & G.S. 10780 11080		3-3-1 WO/Sx & G.S. 13180		3-3-2 W/Sx & G.S. 12980		4-3-1 WO/Sx & G.S. 13080		4-3-2 W/Sx & G.S. 13080		
	2-3-1 WO/Sx & G.S. 13880		2-3-2 W/Sx & G.S. 13780		2-3-2 W/Sx & G.S. 10780 11080		3-3-1 WO/Sx & G.S. 13180		3-3-2 W/Sx & G.S. 12980		4-3-1 WO/Sx & G.S. 13080		4-3-2 W/Sx & G.S. 13080		
	2-3-1 WO/Sx & G.S. 13880		2-3-2 W/Sx & G.S. 13780		2-3-2 W/Sx & G.S. 10780 11080		3-3-1 WO/Sx & G.S. 13180		3-3-2 W/Sx & G.S. 12980		4-3-1 WO/Sx & G.S. 13080		4-3-2 W/Sx & G.S. 13080		

NOTE: WO/Sx & G.S. = WITHOUT ANIMAL T₁ TEST SUBJECT AND SYRINGE GAS SAMPLING
 W/Sx & G.S. = WITH ANIMAL T₁ TEST SUBJECT AND SYRINGE GAS SAMPLING
 10280, ETC. = TEST RUN NUMBERS (SEE TABLE 5)

FIGURE 9. CHAS/SATS MATERIALS TEST MATRIX

The Fortran Fire Analysis Computer program (FACP) was written to calculate the transient concentrations of heat, smoke, and gas hazards generated in a compartment by a burning material as a function of time. Material hazards release rate data, stored on tape processed from CHAS burn tests, were input into the FACP to calculate the individual hazards concentration profiles. The program was generalized to describe the dynamics of heat and combustion products from a burning material in a compartment, treating it as a single zone or as composed of 20 different zones. Figure 10 shows the 20 zone concept used in the CHI program as applied to the CFS.

Only four basic differential equations were used in the computer program describing the following variables: air and compartment wall temperatures, smoke, and gas concentrations (partial pressure). These equations will be presented with a brief explanation of their use in the FACP. A more extensive definition of the computer program used for the CHI compartment modeling will be found in the Part II report.

Several factors effected the development rates of the hazards in each zone extending outward from the material involved in fire. Because of the low thermal capacitance of air, air temperature rose rapidly. Unsteady state thermal gradients were set up in the thermally thick panels used for testing in the CFS, and in the compartment surfaces. The combustion heat of the material and the radiant heat from an external fire (or the radiant heating array in the CFS) was distributed to the compartment air convectively and to the walls and other surfaces by radiative absorption. The FACP differential equations were numerically integrated to calculate the enthalpy changes (air temperatures) in each zone due to the flow of combustion gases from zone to zone and also accounted for the heat exchange between the gases and the walls. The program did not use the material temperature measured in laboratory tests. Smoke and toxic gas levels were also calculated by solving differential equations. The program was formatted to print out the air temperature, smoke transmissions, and concentrations of oxygen, nitrogen, and toxic gases in each of the twenty zones or in a single zone compartment as a function of time during a burn.

Since the number of gaseous hazards evolved by the test panels was limited, only thirteen differential equations were needed in the experimental program and these equations were solved in each of the twenty zones or in the single zone version. Thus the program looped through 260 equations to determine the environment throughout the CFS compartment. The partial pressures of each of the gases were summed to obtain a total pressure in each zone. This total pressure differential between zones drives the fire gases from zone to zone, as shown in Figure 10, until they exit from the compartment.

In the FACP, the unsteady heat flow problem has been based on the change in temperature of materials suddenly exposed to a hot environment. An empirical equation was written which closely fits heat transfer characteristics of a "Grober Plot" (Reference 14). This avoided the need to use partial differential equations.

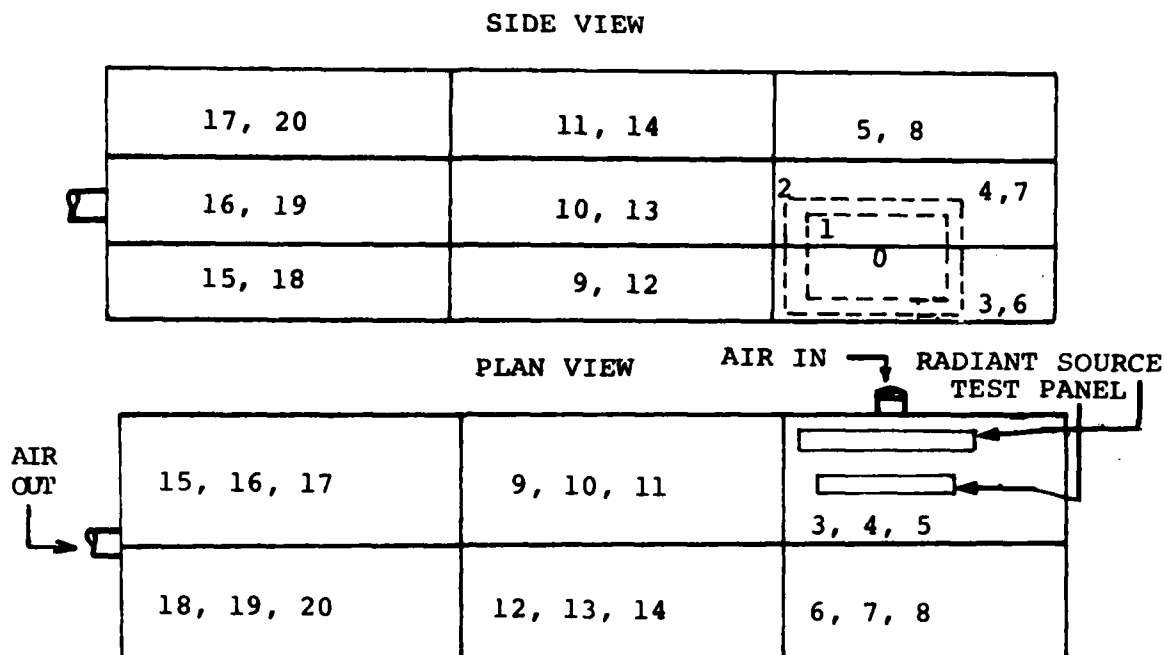


FIGURE 10. 20 ZONE CFS FIRE MODEL

The first differential equation for inside surface temperature was:

$$\frac{dT_s}{d\theta} = \frac{h_e(T_a - T_s) \frac{2A_s}{M_s C_s} \left[1 + \frac{L}{2\sqrt{a\theta}} e^{-\frac{h_e a\theta}{kL}} \right]}{1 + \sqrt{\left(\frac{h_e}{k}\right)^2 a\theta} e^{-\frac{h_e a\theta}{kL}}} \quad (5)$$

Where:

- a = Thermal Diffusivity, ft²/hr
- L = Half Thickness, ft
- θ = Time, Hours
- k = Thermal Conductivity, Btu/hr ft °F
- h_e = Film Coefficient, Btu/hr ft²°F
- T_s = Surface Temperature, °F
- T_a = Air Temperature, °F

Dimensionless Parameters

- $\frac{a\theta}{L^2}$ = Fourier's Modulus
- $\frac{hL}{k}$ = Biot's Modulus
- $\left(\frac{h}{k}\right)^2 a\theta = \left(\frac{hL}{k}\right)^2 \left(\frac{a\theta}{L^2}\right)$
- $\frac{ha\theta}{kL} = \left(\frac{hL}{k}\right) \left(\frac{a\theta}{L^2}\right)$

- A_S = Surface Area, ft^2
 C_S = Specific Heat, $\text{Btu/lb } ^\circ\text{F}$
 M_S = Weight of the Material, lb

The combined convective plus radiative heat transfer coefficient used in the above equations is:

$$h_e = h_a + h_r = h_a + \tau \times 0.1714 \times 10^{-8} \frac{(T_f^4 - T_s^4)}{(T_a - T_s)} \frac{A_f}{A_s} \text{ Btu/hr ft}^2\text{ } ^\circ\text{F}$$

The total heat flux per unit of storage area is:

$$Q = h_e(T_a - T_s) = Q_{\text{CONVECTION}} + Q_{\text{RADIATION}}, \text{ Btu/hr}$$

Where:

- h_a = Convective Heat Transfer Coefficient
 τ = Radiation View Factor
 A_f = Flame Area, ft^2

The smoke data was supplied on the IBM 370 tape as SMOKE units per square meter of sample from the CHAS tests as defined by equation 4 (see CHAS/SATS test procedures), and converted in the program to optical transmittance over a fixed pathlength.

The flow of smoke, S , is assumed to be proportional to the total gas mixture volume flow rate or the total mixture weight flow rate divided by the mixture density, WM/RHO . The flow of smoke into and out of a compartment was:

$$S_{IN} - S_{OUT} = S_1 WM_{IN}/RHO_{IN} - S_2 WM_{OUT}/RHO_{OUT}$$

Thus, the second differential equation used in the FACP for smoke was:

$$dS/dt = (S_{IN} - S_{OUT}) AP/V \quad (6)$$

Where:

- S_1 = instantaneous smoke concentration flowing into the zone
 "particles"/ ft^3
 S_2 = instantaneous smoke concentration flowing out of the zone,
 "particles"/ ft^3
 RHO = air density, lb/ft^3
 WM = weight flow rate of the gas mixture, lb/sec
 S_{IN} = smoke flow into a zone/ ft^2
 S_{OUT} = smoke flow out of a zone/ ft^2
 AP = area of burning panel, ft^2
 V = volume of the zone, ft^3

The zone air temperature differential equation was obtained from equating the thermal capacitance of the air times the rate of change of the air temperature to a summation of the heat flow into or out of the air.

$$Ma C_p dT/dt = \sum (\text{heat flows})$$

Where:

Ma = weight of air in the zone, lb
T = temperature, °F
Cp = specific heat of air, BTU/lb °F
t = time, sec

Thus, the third differential equation became:

$$dT/dt = RT/(PVC_p) \times (Q_{IN} - Q_{OUT}) \quad (7)$$

Where:

p = pressure, lb/ft²
R = gas constant

A differential equation giving the rate of change of the partial pressure of each gas is obtained by differentiating the ideal gas law.

The ideal gas law is:

$$P_i V = M_i R_i T$$

Where:

P_i = partial pressure of gas in mixture, lb/ft²
M_i = weight of gas, lb

R_i = Gas Constant, ft/or
V = Volume of Zone, ft³
T = Absolute Temperature, OR

Differentiating the Equation:

$$\begin{aligned} V \frac{dP_i}{dt} &= M_i R_i \frac{dT}{dt} + R_i T \frac{dM_i}{dt} \\ &= \frac{P_i V}{T} \frac{dT}{dt} + R_i T \left[\frac{M_i}{IN} - \frac{M_i}{OUT} \right] \end{aligned}$$

Then:

$$\frac{dP_i}{dt} = \frac{P_i}{T} \frac{dT}{dt} + \frac{R_i T}{V} \left[\frac{M_i}{IN} - \frac{M_i}{OUT} \right] \quad (8)$$

Where:

M_i = Mass flow rate, lb/sec of each individual gas into the
IN zone or compartment

M_i = Mass flow rate, lb/sec out of the zone or compartment of
OUT each individual gas

Fortran versions of the four differential equations described above have been coded into the CHI computer program in do loop routines which are the same for all zones and gases. Each gas has its own particular gas constant and specific heat. The zones are described by their volumes, surface areas and wall heat transfer characteristics. The program loops through the gas partial pressure equation for each gas in a zone, and it then continues on to the next zone until all of the zones have been analyzed for a time point. This cycle is repeated for each computing time interval to the maximum time specified for the run.

The IBM data tape is used to input data to the Fortran (FACP). The data tape can be input directly into the IBM 370 computer, or the data can be transferred onto a disk for more convenience in accessing the data for repeated running. The computer program flow diagram is shown in Figure 11.

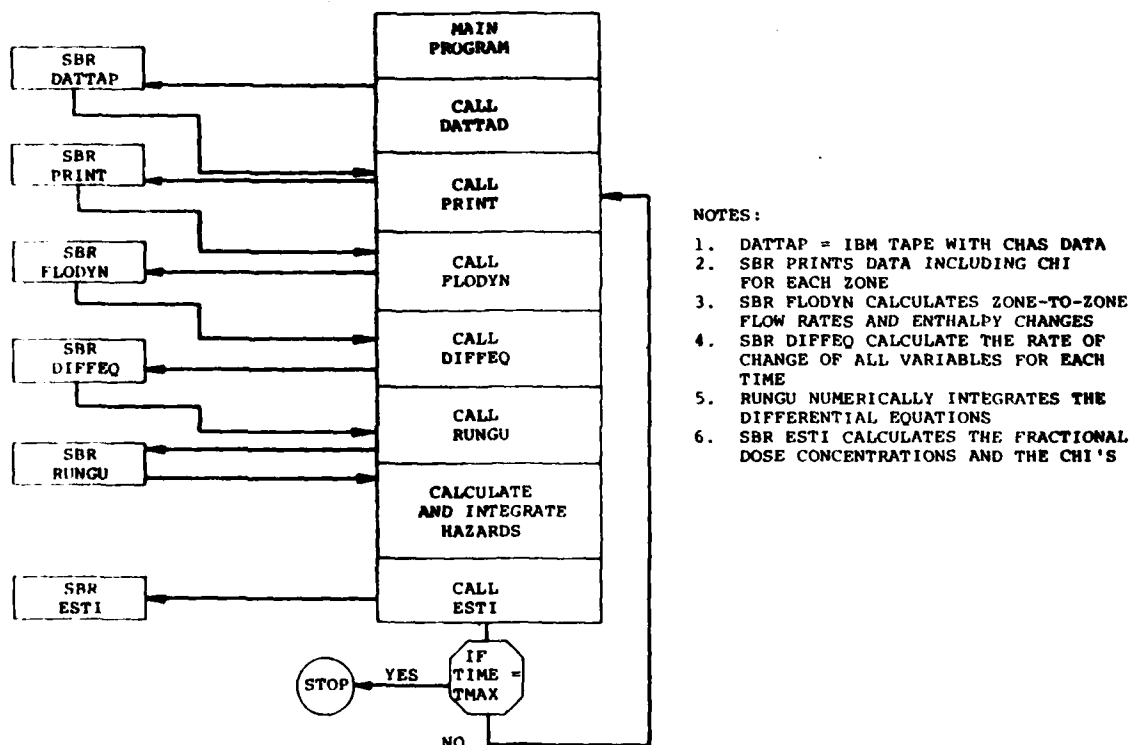


FIGURE 11. 20 ZONE FIRE ANALYSIS COMPUTER PROGRAM FLOW DIAGRAM

The main program calls six (6) subroutines shown on the flow diagram and obtains input data from the IBM/CHAS data tape and a block data section.

When the FLODYN subroutine is called, values for each of the variables for the current time point are known. The total pressure in each zone has been calculated from a summation of the partial pressures in each zone. The flow from a zone to each of the six sides of a zone is calculated in a double do-loop of zones and walls of a zone as a function of the total pressure differential across connecting zones. This total pressure differential between zones drives the fire gases from zone to zone until they exit from the compartment. Each zone has a number and its connection to other zones is defined by a two dimensional array, $P(I,K)$ where I is the zone number and K is the six sides of the zone four walls and the top and bottom of the zone. The number K in the array defines which zone connects to the zone I for each of the six sides. If one of the sides of zone I is a wall, K is set equal to zero, which will indicate that gas flow cannot pass through that surface. The dimensions of the P array are $P(20,6)$ and thus there are one hundred and twenty numbers in the array which define all of the interconnections between zones. Another array $CA(I,K)$ defines the flow coefficient times the flow area for each of the surfaces in the $P(I,K)$ array. A third $KADL(I,K)$ array provides a heat transfer term between zones for each of the surfaces in the $P(I,K)$ array. The $P(I,K)$ and $CA(I,K)$ arrays are used to determine the interconnections and flow coefficients to be used for each surface. The zone to zone flow equation which has been selected for use in the computer program is the Perry orifice equation reported in Reference 15. Thus all of the possible flows are accounted for through the various zone interfaces.

The flow of smoke from zone to zone is made proportional to the total volume flow between zones. The flow of the individual gases is calculated from the ratio of the partial pressure of the gas to the total pressure of the mixtures times the ratio of the molecular weight of the gas to the molecular weight of the mixture.

The differential equations (DIFFEQ) subroutine is capable of calculating the derivatives of up to three hundred (300) differential equations in a double do-loop procedure. The number of equations depends on the number of gases that have been recorded during CHAS burn tests on each specific material. Differential equations describing the variation with time of each zone wall and air temperature, smoke density, and concentrations of CO , CO_2 , H_2O , O_2 and N_2 are numerically integrated for each case. Provisions are included in the program to include up to seven (7) more toxic gases by defining the additional gases using their gas constants (molecular weight and specific heat). Thus, each of the twenty zones are described by up to fifteen equations with a total of three hundred differential equations.

When all of the derivatives in the DIFFEQ subroutine have been evaluated, an IBM double precision differential equations routine (RUNGE KUTTA) numerically integrates the equations to obtain values for the next time point. The values of smoke density, air temperatures and toxic gas concentrations are then evaluated and integrated for each hazard at each time point. The last subroutine calculates the fractional dose for each hazard as well as the CHI for each zone. The CHI methodology ranks the material in a preselected zone (zone 13) in the 20 zone FACP.

ONE ZONE FIRE ANALYSIS PROGRAM - The one zone version of the Fortran Fire Analysis Computer Program solves the same system of equations as the twenty zone version, but treats the compartment volume as a well stirred reactor. All of the environment is uniform with respect to temperature, smoke density and gas concentrations at each time point in the burn scenario. The one zone program reduces the computing time to 1/20 of that of the 20 zone program, but it cannot describe temperature and gas concentration gradients in the compartment.

THERMAL TOLERANCE LIMIT - A thermal hazard limit curve was developed starting with Dr. C. R. Crane's equation described in Reference 16. This equation is a least squares curve fit and extrapolation of pertinent time-to-incapacitation data for normal individuals.

The equation derived by Crane is:

$$t_c = Q_0/T^{3.61} \quad (9)$$

Where, t_c = time-to-thermal collapse, in minutes,

T = air temperature, °C

Q_0 = 4.1×10^8 , a statistically derived proportionality constant related to calories the body can absorb before collapse.

All of the data points reported in Reference 16, were entered in a generalized curve fit routine using the Hewlett Packard 9825A computer. From this a more representative equation was derived from the available empirical data and used in the FACP in its integrated form. Use of the integrated form was necessary because the temperature constantly varies in a cabin fire. Therefore, by selecting small time intervals, over which the temperature may be nearly constant, the accumulation of heat can be integrated. If this equals Q_0 at some time, t , then $t = t_c$. The equation resulting from this new curve fit was as follows:

$$T_i = 5.33 \times 10^8 / [(F \times 1.8) - 32]^{3.66} \quad (10)$$

T_i = time to incapacitation, minutes

F = air temperature, °F

Figure 12 shows a plot of the T_i - Temperature curve based on Equation 10.

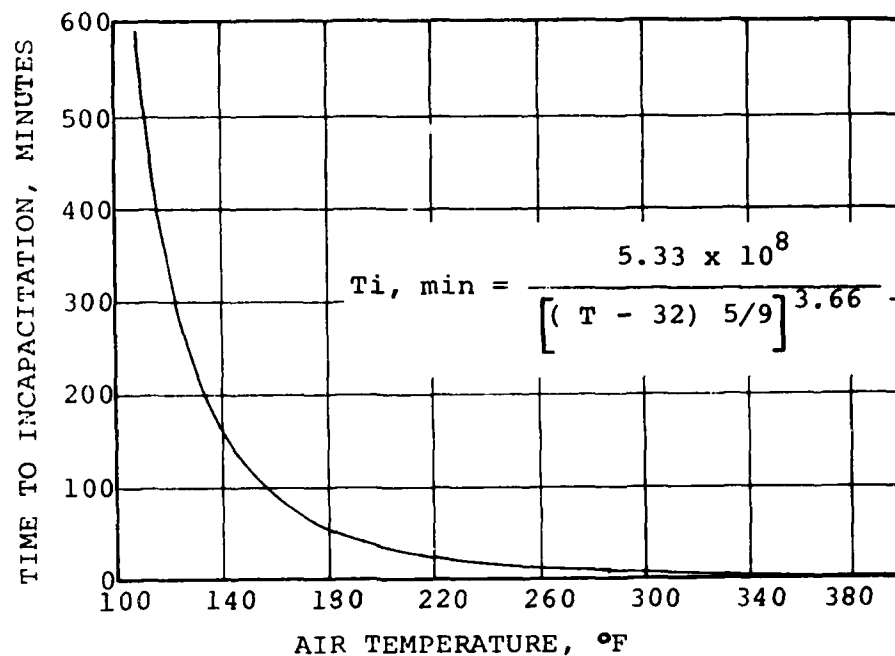


FIGURE 12. TIME TO INCAPACITATION VS TEMPERATURE

TOXIC GAS TOLERANCE LIMITS - A toxic gas algorithm was derived for use in the FACP to calculate the concentrations of important gases accumulating in a cabin as a material burns. As with the temperature hazard, it was necessary to relate toxic gas emissions to physiological incapacitation as the endpoint. The algorithm was simplified for use by calculating the ratio of the dose building up to the incapacitation dose.

In classical toxicology, physiological effects are commonly stated in terms of a toxicant dose (weight) absorbed by the body that results in an endpoint, usually lethality is for a statistical number of test subjects. Various endpoints are used, i.e., LD₅₀ the lethal dose for 50% of all subject tested. Other lethal dose expressions such as LD₁, LD₂₅, LD₉₉ are sometimes used in which the subscript relates to the percent of test subject population giving a lethal response.

In fires, the physiological hazard involves the inhalation and absorption of toxic combustion products through the lungs. A dose is often stated as the concentration by volume of the toxic gas in air resulting in lethal response at the 50% level (LC₅₀). This expression or similar lethal dose measures were not used to develop the CHI toxic hazard algorithm. Hence, a dose-response relationship based on the inhaled concentration of a toxic gas in air required to cause Ti was selected as a more conservative endpoint than death.

To develop this approach, Ti limits for exposures to high concentrations of each toxicant for times up to 5 minutes (scenario definition) were needed. An examination of the literature uncovered only limited useful short term exposure data for a few gases. Even less information was found relating Ti to the concentrations of most other gases emitted by plastic materials.

Several assumptions were made to simplify the algorithm: (1) the toxic endpoint (Ti) was dependent only on the additive toxic doses of each gas in the combustion mixture [possible synergistic (greater than additive), or antagonistic (mutually canceling or subtractive) interactions were not included]; (2) only a limited number of toxic gas species, most commonly found in combustion products, were needed to compare and rank cabin materials for toxic hazard potential, and calculation of a CHI; and, (3) the short term Ti-dose limit relationship developed for systemic toxic gases (e.g., CO, HCN, etc.) also apply for irritant gases (HF, HCl, aldehydes, etc.), and did not take into account variations due to the state of health or body weights of the occupants exposed to the hazards.

An analysis of the human survival limits of 15 toxic gases commonly found in plastic combustion mixtures was conducted. The following equation was used to determine initially the estimated 5-minute hazard dose limit, (HL)₅ for each gas:

$$(HL)_5 = \frac{480 \times TLV \text{ (ppm)}}{t} \quad (11)$$

Where: 480 = number of minutes in an 8 hour work day

TLV = threshold limit values (ppm) based on industrial hygiene experience for an 8-hour working day.

t = maximum scenario exposure time (5 minutes)

The literature was surveyed to find data for each gas closest to a 5-minute survival time. Knowing the physiological effects and modes of action, interpolations were made where the data was not sufficiently specific. The result for each gas was compared with the estimated (HL)₅ as determined by the equation 11. In ten of the 15 cases the equation appeared to reflect an acceptable limit. In the other five cases further adjustments of the (HL)₅ appeared to be necessary, based on mechanisms of action, and the judgement of the analyst. Table 3 shows the results of these analyses.

TABLE 3
HUMAN SURVIVAL LIMITS ANALYSIS

GAS HAZARD	TLV PPM	(HL) ₅ DOSE ESTIMATED BY EQUATION 11	
		PPM	%
NO ₂	5.0 (c)	480	0.0480
HCl	5.0 (c)	480	0.0480
HCl	-	50(J)	0.005(J)
HF	3.0	288	0.0288
HBr	3.0	288	0.0288
SO ₂	5.0	488	0.0488
SO ₂	-	350(J)	0.0350(J)
H ₂ S	10.0	960	0.0960
H ₂ S	-	600(J)	0.0600(J)
COCl ₂	0.1	9.6	0.00096
COF ₂	0.1 (est)	9.6	0.00096
NH ₃	25.0	2400	0.2400
HCHO	2.0 (c)	192	0.0192
HCHO	-	100(J)	0.0100(J)
CH ₃ CHO	100.0	9600	0.960
Acrolein	0.1	9.6	0.00096
CO	50.0	4800	0.4800
CO ₂	5000.0	480,000	48.000
CO ₂	-	150,000(J)	15.000(J)
HCN	1.0 (est)	96.0	0.00960

(c) = ceiling value
est = estimated
J = adjusted value

The breathing time (fire gas exposure time) needed to produce a Ti varies inversely with the concentration of each toxic gas. Thus, the dose, Di, resulting in a Ti when a constant concentration, C, is inhaled may be expressed as:

$$D_i = C \text{ (ppm or \%)} \times T_i \text{ (sec)} \quad (12)$$

Solving equation 12 for Ti using C as the independant variable:

$$T_i \text{ sec} = \frac{D_i \text{ (\% - sec)}}{C \text{ (\%)}} \quad (13)$$

The Di values for use in equation 13 are equivalent to the CTi products obtained by multiplying the (HL)₅ values for each gas listed in Table 3 by the 300 second breathing time estimated to result in a Ti. Thus, equation 13 can be expressed as:

$$T_i \text{ (sec)} = \frac{(HL)_5 \text{ (\%)} \times 300 \text{ sec}}{C \text{ (\%)}} \quad (14)$$

To illustrate, the (HL)₅ concentration (from Table 3) is 0.48% (4800 ppm). Substituting into equation 14:

$$T_i \text{ (sec)} = \frac{0.48 \times 300}{C(\%)} = \frac{144}{C(\%)}$$

Where: 144 = K = Constant derived from TLV data.

Figure 13 shows a plot of the CO hazard limit curve relating % concentration to T_i. This curve is unique as used in the FACP and includes the (HL)₅ coordinates, 0.48% CO at 300 sec. T_i. To cross check the validity of the CO curve derived for the CHI program by Dr. Gaume, a comparison was made with the human absorption relationship for inhalation of high levels of CO reported by Peterson and Stewart in Reference 17. The equation presented by these investigators describes the rate of COHb increase in the blood per liter of air breathed:

$$\text{Log (\%COHb/liter air)} = 1.036 \log (\text{ppm CO inhaled}) - 4.4793 \quad (15)$$

Using the incapacitation limit of 46.5% COHb calculating the liters/min of air breathed at different levels of activity, equation 15 was modified to the general form of equation 13:

$$T_i \text{ (sec)} = \frac{46.5 \times 60}{10^{1.036 \log \text{ppm} - 4.4793} \times V} \quad (16)$$

which simplifies to:

$$T_i \text{ (sec)} = \frac{8.406 \times 10^7}{10.864 \log \text{ppm CO} \times V}$$

Using equation 16, a family of concentration-T_i curves were plotted at different respiration rates dependant on level of activity for comparison with the hazard limit curve selected for the CHI calculation.

Based on the modified Peterson and Stewart relation (equation 16), a simple calculation shows that at a level of 42.56 liter/min respiration rate, the resulting curve is nearly identical to the CHI (Guame) curve, indicating the conservative nature of the latter.

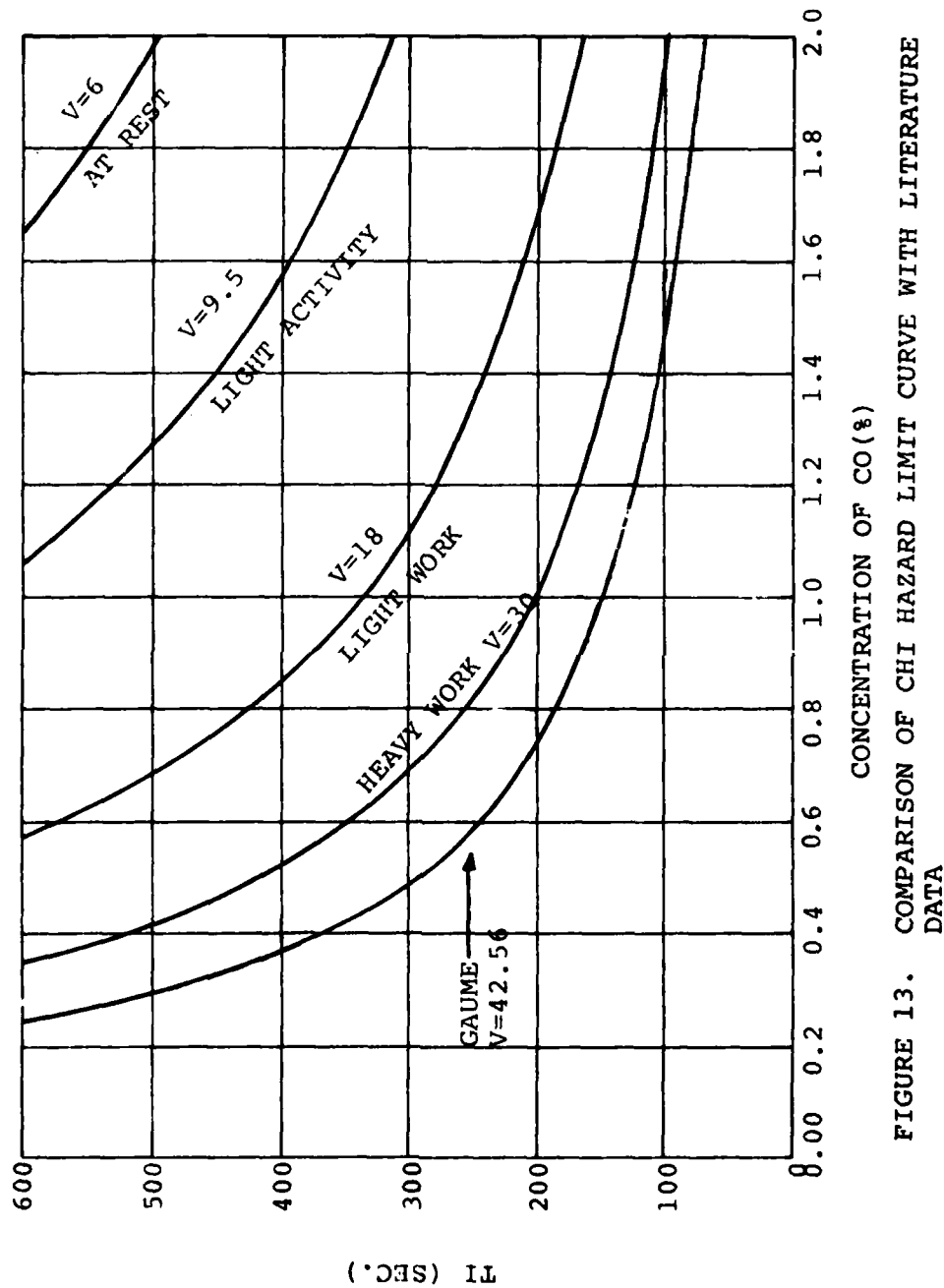


FIGURE 13. COMPARISON OF CHI HAZARD LIMIT CURVE WITH LITERATURE DATA

(The top 5 curves were plotted from the Peterson & Stewart equation where: V = human ventilation rate, liter/min at various levels of activity and COHb (accumulated in blood) = 46.5% saturation at T_i .) as in Equation 16.

In a fire, however, the concentration of gases vary with time in accordance with the mass burning rate, availability of oxygen and other factors. Although relationships such as equations 14 and 16 have been derived from exposures to constant concentrations, they can be used for cases involving varying concentrations if concentration-burn time profiles are known. These profiles were measured in CHAS. The integral of the release rate curve over each burn time interval is used to calculate the burn time at which a T_i would occur. When the integral (area under the release rate profile) equals K (CT_i product) for a particular gas the burn time is T_i . Thus for CO:

If $\int_0^t C_{CO} dt$ is less than 144, incapacitation (T_i) will not occur, but if

$\int_0^t C_{CO} dt$ equals 144, incapacitation (T_i) occurs, and the

corresponding burn time is established.

SMOKE (VISIBILITY) HAZARD LIMITS - A crude first approach to the problem of developing an escape time curve for the effects of reduced visibility through smoke is shown in Figure 14. The rationale used in developing this approach was based on how far an individual can see an illuminated emergency exit sign at various smoke. In the absence of definitive data for the biological effects associated with the inhalation of smoke, the hazard limit curve for smoke was based only on light attenuation.

Allard's Law, Reference 18, provides a means to calculate the illuminance, (foot candles), at the observer's eye from a light of a given luminous intensity (candles), at a distance from the observer. The equation expressing Allard's Law is:

$$E = IT^D/D^2 \quad (17)$$

Where: E is the illuminance at the observer's eye in foot candles

I is the intensity of the source light in candles or candela

D is the distance between the source light and the observer in feet

T is the transmittance of the attenuating smokey atmosphere, or transmittance per unit foot.

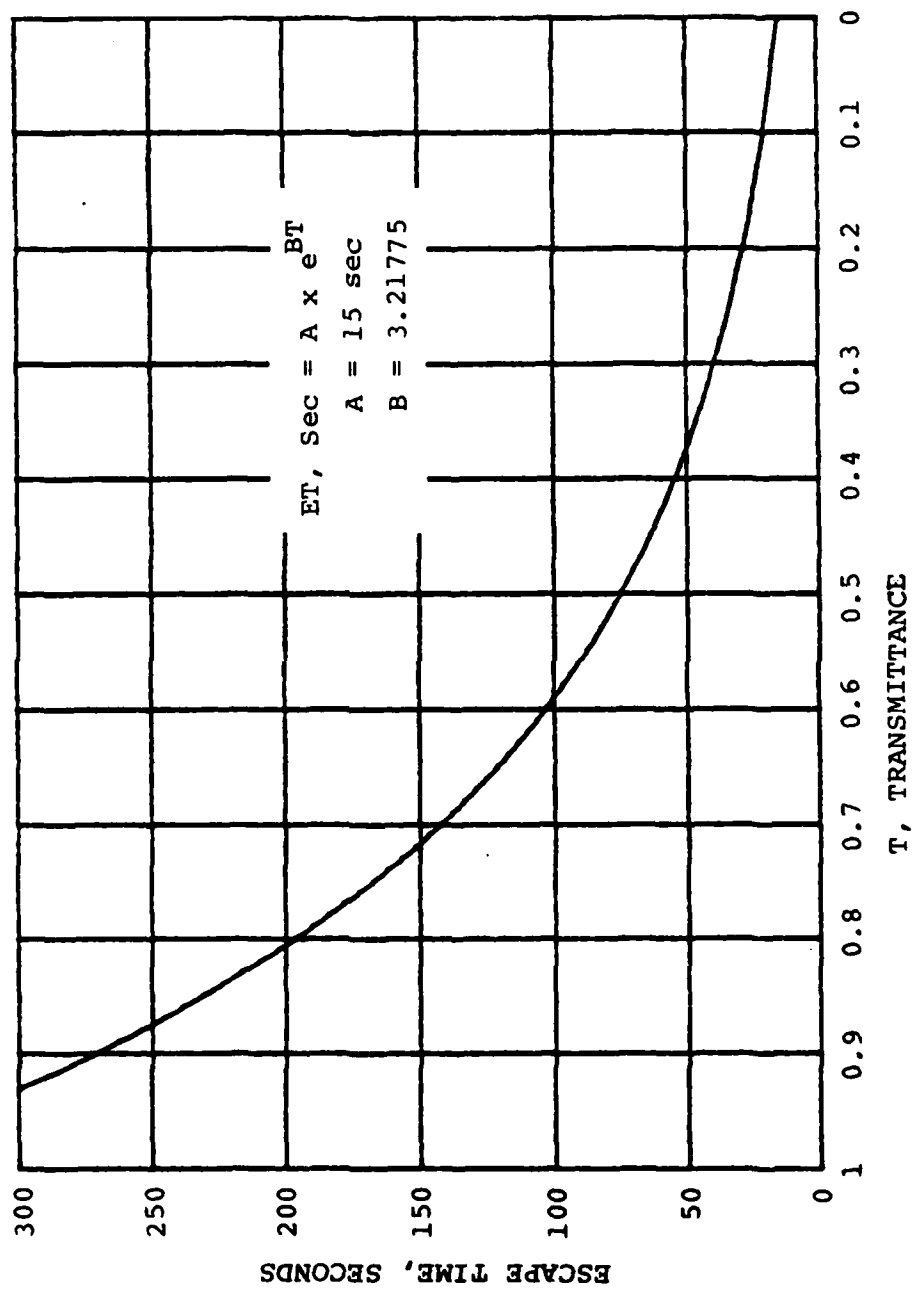


FIGURE 14. ESCAPE TIME VERSUS LIGHT TRANSMITTANCE THROUGH SMOKE

Based on this law it was calculated that a normal observer can see a lighted cabin exit sign 100 feet away when smoke transmittance is 93.1% per unit foot. This value was used to locate one point on the curve in Figure 14 defining escape time as 300 seconds. Another point is located at 15 seconds escape time in complete darkness, since this was a reasonable time required to feel the way to an exit 34 feet away from a typical seat nearest that exit. As indicated by the equation shown in Figure 14, the escape time versus light transmission was assumed to be exponential. This equation was used in the calculation of CHI, but not in an integrated dose rationale as with the toxic gases and air temperature hazards.

However, a further need to de-emphasize the role of smoke in CHI calculations based solely on light attenuation or visibility became apparent. Evaluations showed that smoke would over-ride the fractional dose contributions of the other important hazards to such an extent that materials ratings would be based only on smoke. Therefore, the calculation of fractional dose for smoke in the FACP was arbitrarily limited to a maximum of 0.4 in all CHI determinations.

CHI CALCULATION

The FACP calculates the fractional "effective dose" (FD) for all gases, smoke, and cabin air temperature at short time intervals over burn profiles of 5 minutes. The FACP then prints out the FD's for each gas and the FD sum for the mixture at each burn time intervals:

$$FD (mix) = \sum \left(\frac{\int C_1 dt}{K_1} + \frac{\int C_2 dt}{K_2} + \dots + \frac{\int C_n dt}{K_n} \right) \quad (18)$$

When the FACP print out shows that the FD (mix) equals 1, the burn time interval from $t = 0$ to $t = T_i$ defines the escape time or CHI for the materials being tested. A graphical plot of each hazard and the mixture will give a view of the specific hazards contributing to the mixture escape time limit.

In those cases where the FD (mix) of a material does not reach the hazard limit of 1, the CHI may be stated as "greater than 300 sec", or the computer program may be rerun introducing a larger area of material if it becomes necessary to compare two such materials for selection by relative ranking. The value of the 5 minute fractional dose for the mixture may also be used to rank two such materials.

CABIN FIRE SIMULATOR (CFS) TESTING

The full-scale tests performed in support of the Combined Hazard Index Program were conducted in the Douglas Cabin Fire Simulator (CFS). The objective of these tests was to develop the FACP and to demonstrate the correlation of laboratory predicted hazard concentrations with those actually measured in the CFS (typical of large scale cabin fire). The interior of the CFS was configured as shown in Figure 15. For interface with the computer program, the 18 major instrumentation points were located in the center of each of the cabin zones. The baseline test aluminum panel and the 4 x 6 ft test samples were

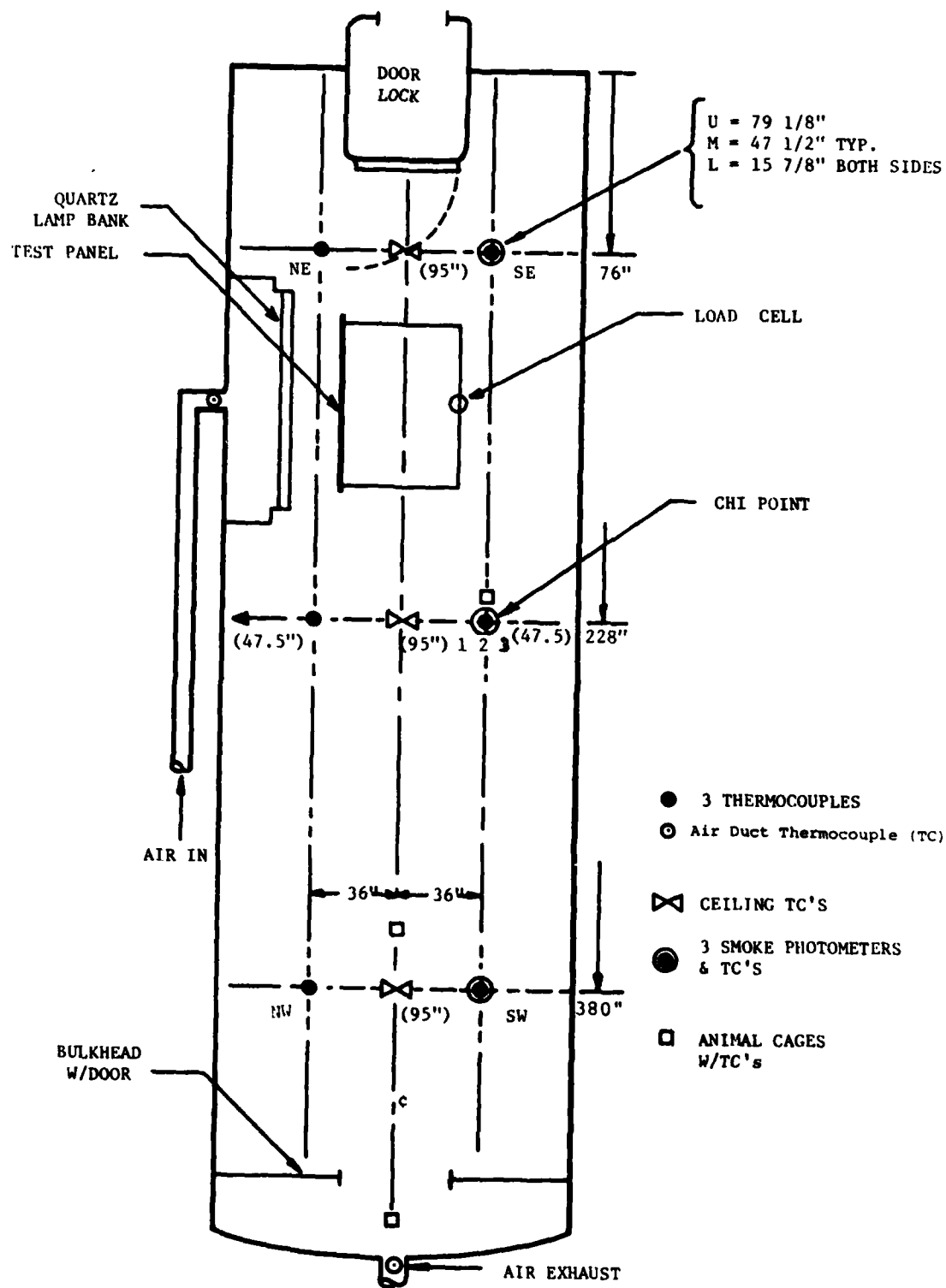


FIGURE 15 PLAN VIEW OF CFS TEST CONFIGURATION

exposed to the radiant flux emitted from 16 radiant quartz lamp modules arranged to produce as uniform a heat flux as possible on the exposed panel. (Figure 16.) The test sample was mounted on a weighing fixture with the exposed face 32 inches from the quartz lamps.



FIGURE 16. RADIANT HEATER ARRAY

The temperature of the air was recorded from thermocouples located in the entry and exit air ducts. The air temperature was also measured one inch under the ceiling on centerline between the main temperature measuring trees. Air entered the chamber at 875 cfm flow at ambient temperature through a plenum chamber mounting the radiant source. This air flowed uniformly around all of the radiant elements providing the necessary cooling for the power cables and ceramic reflectors. After flowing through the CFS, the air exited through a simulated door opening in the end bulkhead and out through a 6-inch duct in the center of the end dome of the CFS.

Specimen attachment to the frame was made in the first 3 tests with 3/16 machine screws, 5/8 in. diameter washers and nuts on the frame side. This method of attachment was modified in the latter 9 tests by clamping the panel in a steel frame with four edge bars as shown in Figure 17. The mounting frame was held in position by a four bar linkage system restrained by a 0-50 lb. load cell on the side opposite from the sample, the output of which was recorded by the computer data system. The weighing ability of this system was validated by adding and removing weights within the range of expected weight loss and its performance was within .05 lb.

The gases monitored in real time during each run, using dedicated instruments specific for detection of each gas, were CO, CO₂, O₂, CH_x, and HCN at the CFS exhaust. CO, CO₂ and O₂ were also monitored in real time at the CHI point location with the sampling line inlet placed near the animal test chamber. Data read from all of the real time gas monitors, thermocouples, smoke photometers, and differential pressure airflow orifice meters were recorded by a PDP-15 computer data acquisition system. Other gases monitored using bubblers (standard glass impingers) located at the CHI sampling point were HCl, HF & aldehydes. These bubblers were mounted in an insulated box to protect them from heat building up during each test in the CFS. Twelve bubblers were connected in pairs on a manifold inside the box; one set contained sodium hydroxide solution for absorption and subsequent analysis of HCl and HF, and the other set contained the aldehyde absorption reagent solution (see under CHAS/SATS Test Procedures). Flow rates of CFS atmosphere were sequentially taken at timed intervals into each pair of bubblers by remote control of electrically operated solenoid valves. This assembly is shown in Figure 18.

ANIMAL TESTING IN THE CFS- In the first series of tests, six open mesh driven split wheel rat cages employing sensors of the same design used in the laboratory SATS tests were placed in the zone locations shown in Figure 15. The boxes did not shield the rats from heat so that they were exposed for approximately one half hour after testing while the chamber cooled for entry. Data collected during the test was not conclusive to say whether the rats died from toxic gases, or heat, or a combination of both. For the final three materials, the exposure chambers were redesigned as closed polycarbonate boxes which were covered with insulation blankets composed of two inches of fiberglass insulation lined with a silicone material on the inside, and covered on the outside with a metallized silicone material. The CFS air was pulled through two large inlet tubes which penetrated the insulation blankets and carried the air into the exposure chambers. The air was mixed by deflectors inside the chamber and exited through a single outlet which was connected to the vacuum pump. The pump was situated on the cage platform outside the insulation blanket to avoid adding the pump's heat to the exposure chamber. Pump capacity was approximately sixteen liter per minute. Figure 19 shows the insulated animal test chambers.

The time to incapacitation (Ti) method of monitoring the rats developed by the FAA (Reference 19) was used. The output from the contact bars were recorded on an 8-channel ASTRO MED SUPER 8 hot pen recorder with one channel dedicated to each rat. The temperatures in the four chambers (six rats) were multiplexed on the seventh channel and the temperature in each chamber was recorded for three seconds so that each chamber temperature was sampled every twelve seconds. The

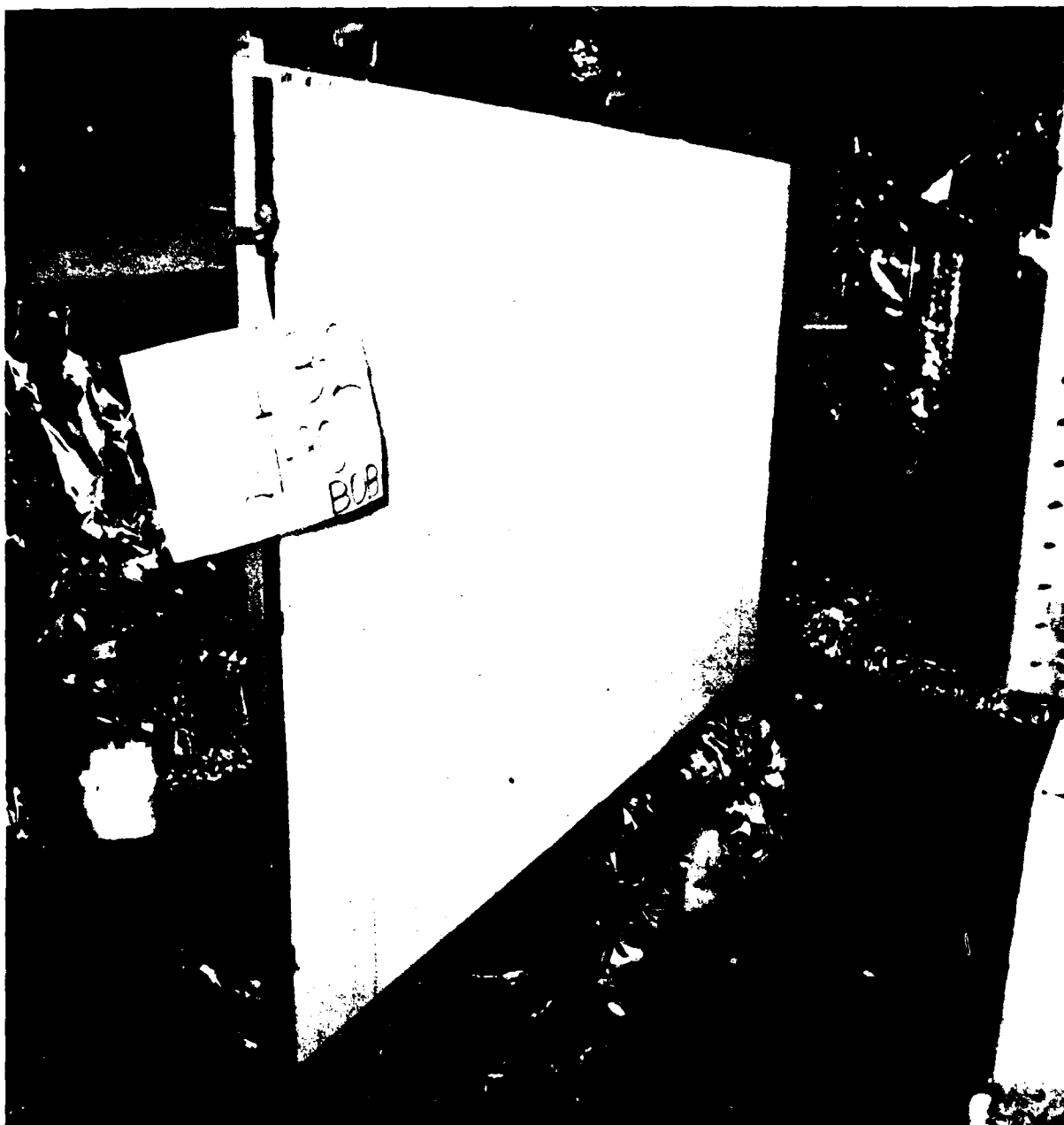


FIGURE 17. PANEL MOUNTED IN FRAME IN PREPARATION
FOR CFS TEST

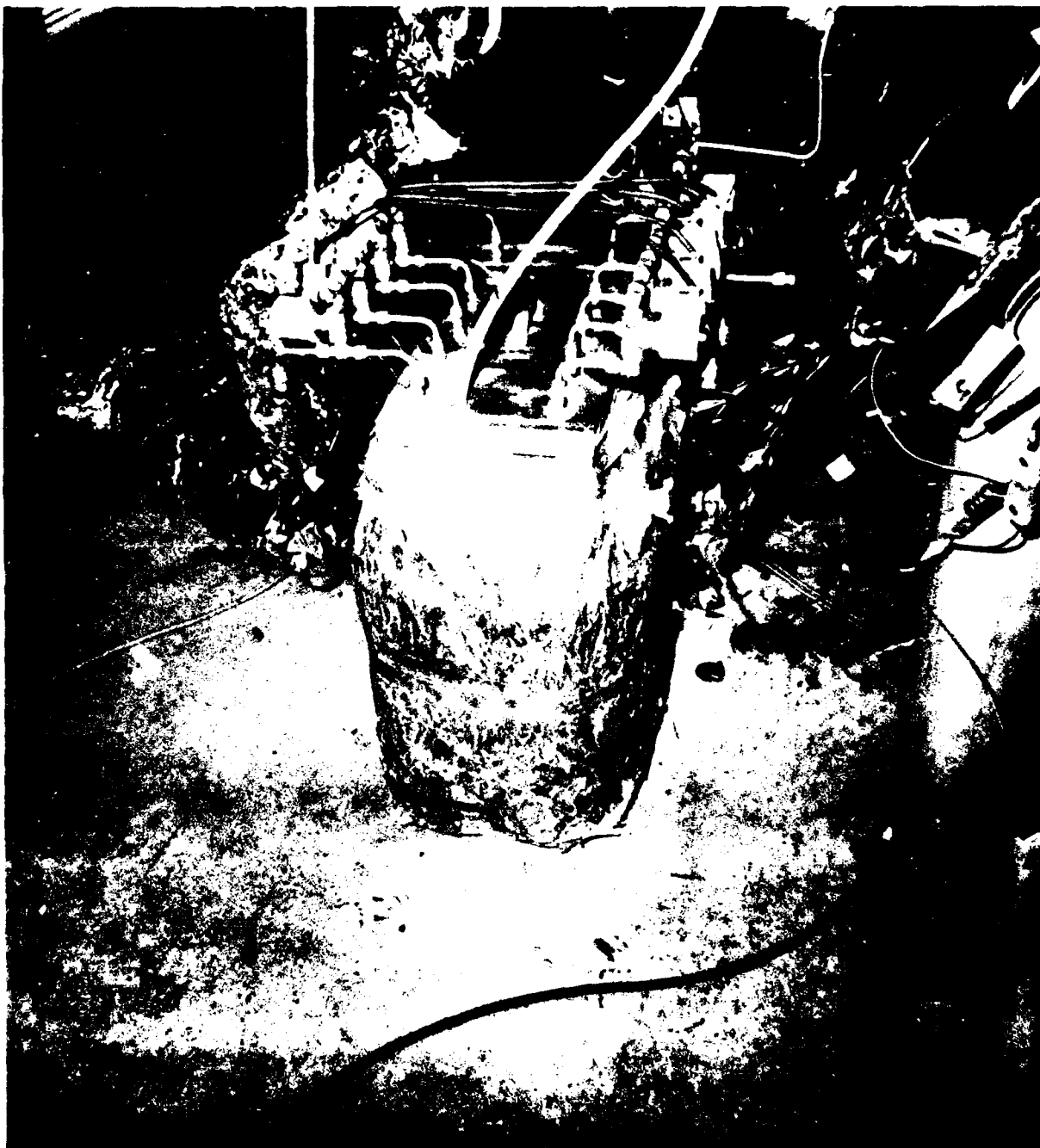


FIGURE 18. SOLENOID VALVE CONTROLLED GAS SAMPLING UNIT

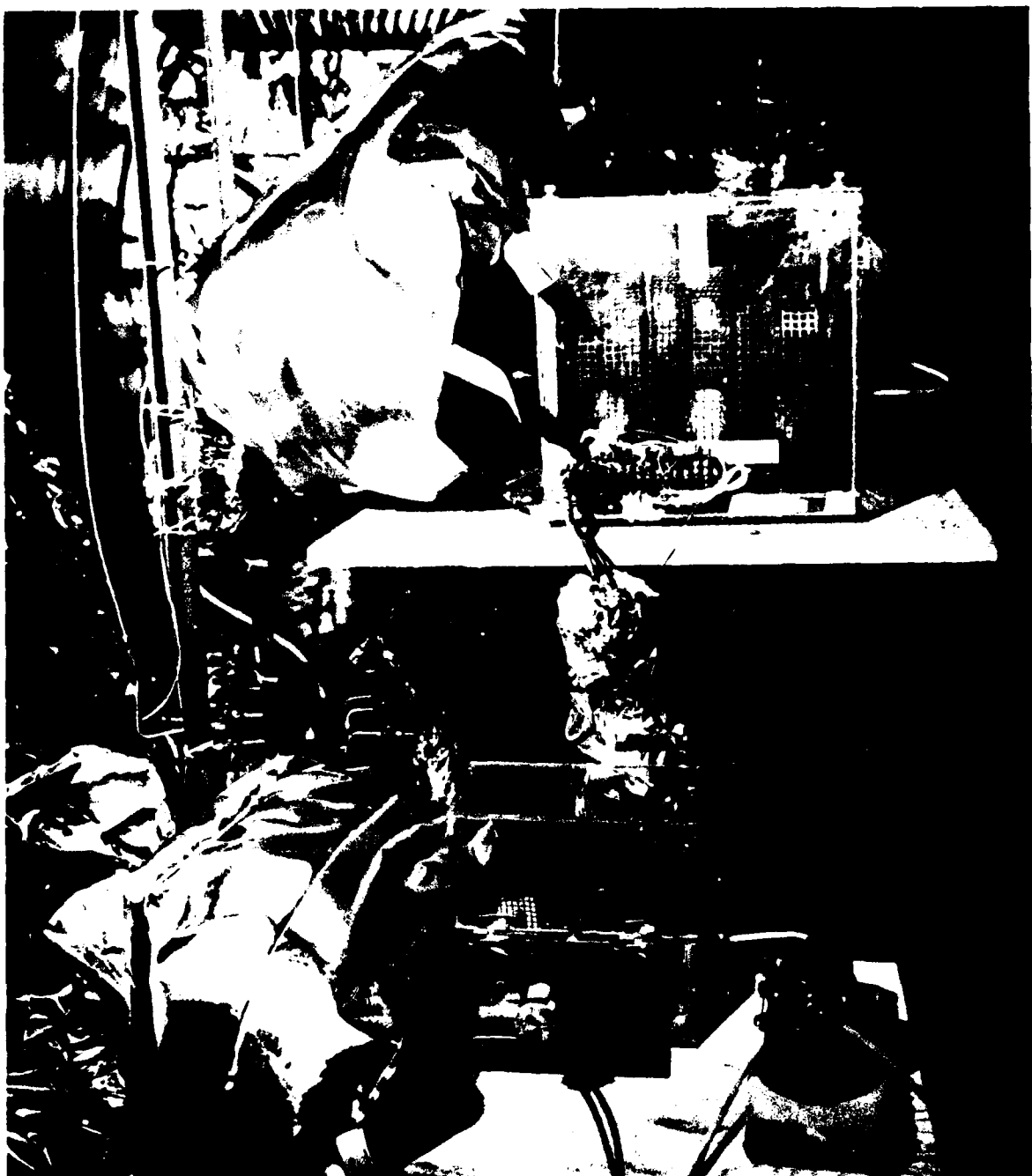


FIGURE 19. INSULATED ANIMAL CHAMBERS (Photograph shows insulation removed)

The procedure adopted during a run included turning off the vacuum pumps pulling air through the chambers, when maximum CO concentration was reached as in the laboratory CHAS/SATS testing. This procedure was adopted in order to retain maximum gas concentration, since CFS ventilation was continued until re-entry could be made after the CFS had cooled.

COST EVALUATION

The costs of using the CHAS and the CHI Fire Analysis Computer Programs were evaluated in terms of: (1) capital equipment costs (CHAS only) and (2) testing costs.

Figure 20 shows the costs (in terms of labor hours) of testing a material at one heat flux using the CHAS methodology. Computer costs will vary depending on individual organization computer equipment. The one zone CHI will be approximately 1/20th the time of running of a 20 zone CHI calculation. As indicated, the microchemical analyses require the longest time and the number of these, if any, will depend on the test objectives.

Capital equipment costs, exclusive of the laboratory facilities required to house the CHAS, and the assembly costs based on 1979 prices, are listed in Part 2 of the CHI Report.

An estimate of CHAS equipment outlay and operational costs is summarized as follows:

Capital Costs

CHAS Equipment Costs For R/D Program \$87,756 (1979)

Labor Hours (Four Samples per day)	CHI CALCULATION	
	1 Zone	20 Zone
9 hours X \$30/hr.*	\$270	\$270
Computer Time	<u>50</u>	<u>350</u>
Total Labor (4 samples) =	\$320	\$620
Per Sample Cost =	\$ 80	\$155

* Cost figure is arbitrary and will vary depending on organization.

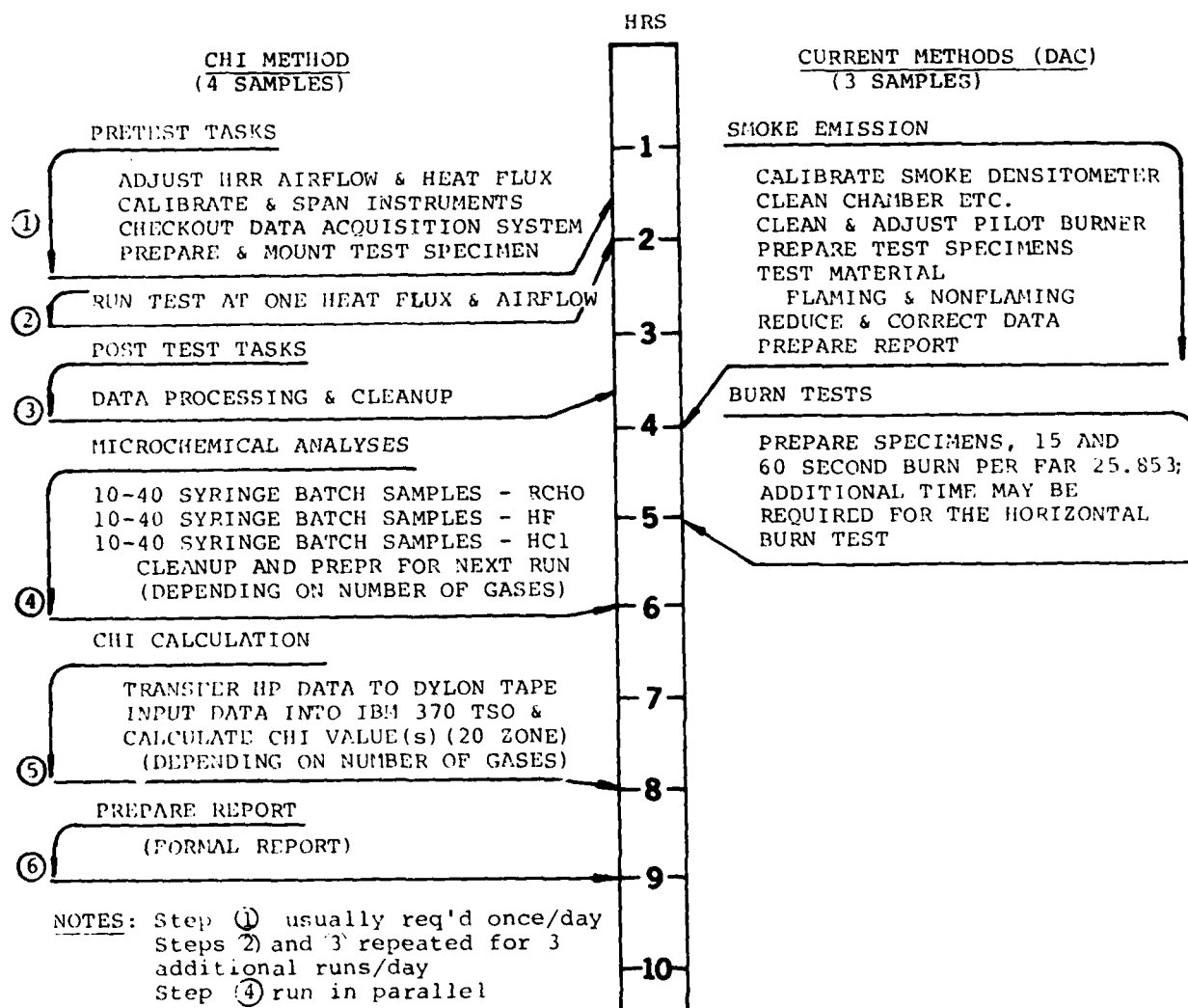


FIGURE 20. MATERIAL PRODUCTION RUN LABOR COST COMPARISON

IV. DISCUSSION OF RESULTS

CHAS/SATS TEST RESULTS

PANELS 1, 2, 3 and 4 - Early in Phase 2 of the development program, test Panel No. 1 (see Table 2) was extensively tested in the CHAS/SATS. The system used in this earlier work was not equipped with the flexible disk memory or an NO/NO_x monitor and employed an O₂ monitor much slower in response than the instrument used later in testing panels 2, 3, and 4. Nineteen tests were conducted in this version of the CHAS/SATS; data from 12 of these tests (free of instrument malfunctions) are summarized in Table 4. During this phase animal tests were conducted on 9 runs at 5 W/cm² to develop the SATS test procedure. Animal tests were not conducted at other heat flux levels since the large scale tests of Panel No. 1 were conducted in the CFS only at 4.41 Btu/ft² sec (5 W/cm²). At that time, the data acquired and processed by the HP-ADAS was recorded on cassette tape. These data were transferred via the Dylon formatter to IBM 370 tape for use in developing the 20 zone FACP. The data generated in these runs differed from later test data in that the HRR data were calculated from the DTP response instead of from O₂ consumption calorimetry. The data from Panel 1 was reprocessed and updated for one run using the O₂ consumption calorimetric method for calculating the HRR, even though the oxygen depletion was measured with the slower response O₂ monitor. For this example, a series of plots showing representative hazards release rate profiles of Panel No. 1 are shown in Figure 21. These illustrate the output of the CHAS instrumentation. In digitized form, the data from each hazard plot were used to calculate the CHI using the FACP.

The plots also clearly show the burning sequence exhibited by this sample when exposed to an external 4.41 Btu/ft² sec (5 W/cm²) radiant heat flux. Ignition occurred in the first few seconds. Flames spread rapidly over the front surface involving the PVF/PVC decorative and adhesive layers shown by the first peak in the release rate curves. This was followed by a reduced burning rate as evidenced by the valley centered at 1 minute, as shown in most of the hazards profiles.

The second burn peak observed near 1.5 minutes correlated with a visually observed increase in flaming as the radiant heat penetrated into the interior, igniting the back surface decorative layers. All of the hazards profiles (Figure 21(a) through (j)) did not exhibit the same degree of resolution of the burn episodes represented by the twin release rate peaks.

The best separation was achieved by the smoke photometer. This was understandable since the detector response time is very short and the photometer is located at the stack exit. The CO gas monitor showed the next most rapid response, followed by the CO₂, combustible gas, and oxygen monitors. The HCN monitor showed the least capability for resolving fast evolution transients. Other tests have shown that this variation in performance was caused by diffusional intermixing of rapidly changing gas specie concentrations with the air stream flowing through the lines from the gas sampling tube in the HRR to each monitoring instrument. The effect could not be eliminated but was reduced by keeping the gas leads as short as possible and reducing the tubing diameter. The increase in CO from 3 to 7 minutes (Figure 21(c)) indicated a smoldering phase in this test.

TABLE 4
SUMMARY OF HAZARDS RELEASED BY CHI PROGRAM TEST PANEL NO. 1

RUN NO.	SAMPLE NO.	HEAT FLUX W/CM ²	SAMPLE WEIGHT GRAMS	CHAR YIELD Y _C %	HEAT RELEASE		TOTAL 3 10 MIN KW/M ² (MIN)	TOTAL 3 10 MIN SSU/M ² (MIN)	TOTAL 3 10 MIN SSU/M ²	TOTAL CO ₂ IN 10 MIN GRAMS/M ²	TOTAL CO IN 10 MIN GRAMS/M ²	TOTAL HCN IN 10 MIN GRAMS/M ²	TOTAL NO. (HGX) IN 10 MIN GRAMS/M ²	TOTAL SAMPLED GAS-10 MIN GRAMS/M ²
					PEAK KW/M ² (MIN)	TOTAL 3 10 MIN KW/M ²								
43	1	3.5	272.7	64.4	40 (3.7)	213	m.f.	m.f.	674	435	152	1.8	n.d.	46
46	1	3.5	267.2	56.2	51 (3.7)	338	84 (1.5)	214	1243	1259	245	3.2		52
76	1	4.0	282.5	60.0	48 (3.2)	290	92 (0.8)	167	1096	851	149	1.6		53
78	1	4.0	274.6	66.9	37 (3.7)	207	66 (1.7)	152	1102	890	162	0.9		92
79	1	4.0	282.8	53.0	42 (3.7)	282	76 (1.1)	138	1224	1012	162	m.f.		152
47	1	5.0	274.9	51.6	68 (2.2)	402	177 (0.8)	280	1111	1292	235	2.7		60
48	1	5.0	272.3	49.0	72 (2.4)	470	170 (0.8)	264	1158	1414	216	2.5		51
49	1	5.0	270.5	46.0	70 (2.4)	417	177 (0.8)	264	1379	1450	270	3.0		51
50	1	5.0	274.1	54.8	80 (2.0)	415	136 (0.8)	212	2273	1594	372	3.3		51
51	1	5.0	278.9	49.8	72 (2.0)	413	165 (0.8)	299	1711	1190	301	2.9		63
77	1	6.0	278.1	47.9	73 (2.0)	447	157 (0.6)	219	1651	1514	134	0.9		64
81	1	6.0	278.8	44.4	80 (2.0)	453	120 (0.7)	203	1505	1207	112	1.2	n.d.	76

1 = Pilot light quenched during the run

m.f. = Malfunction, no data recorded

n.d. = Not determined, monitor not available at time tests were made.

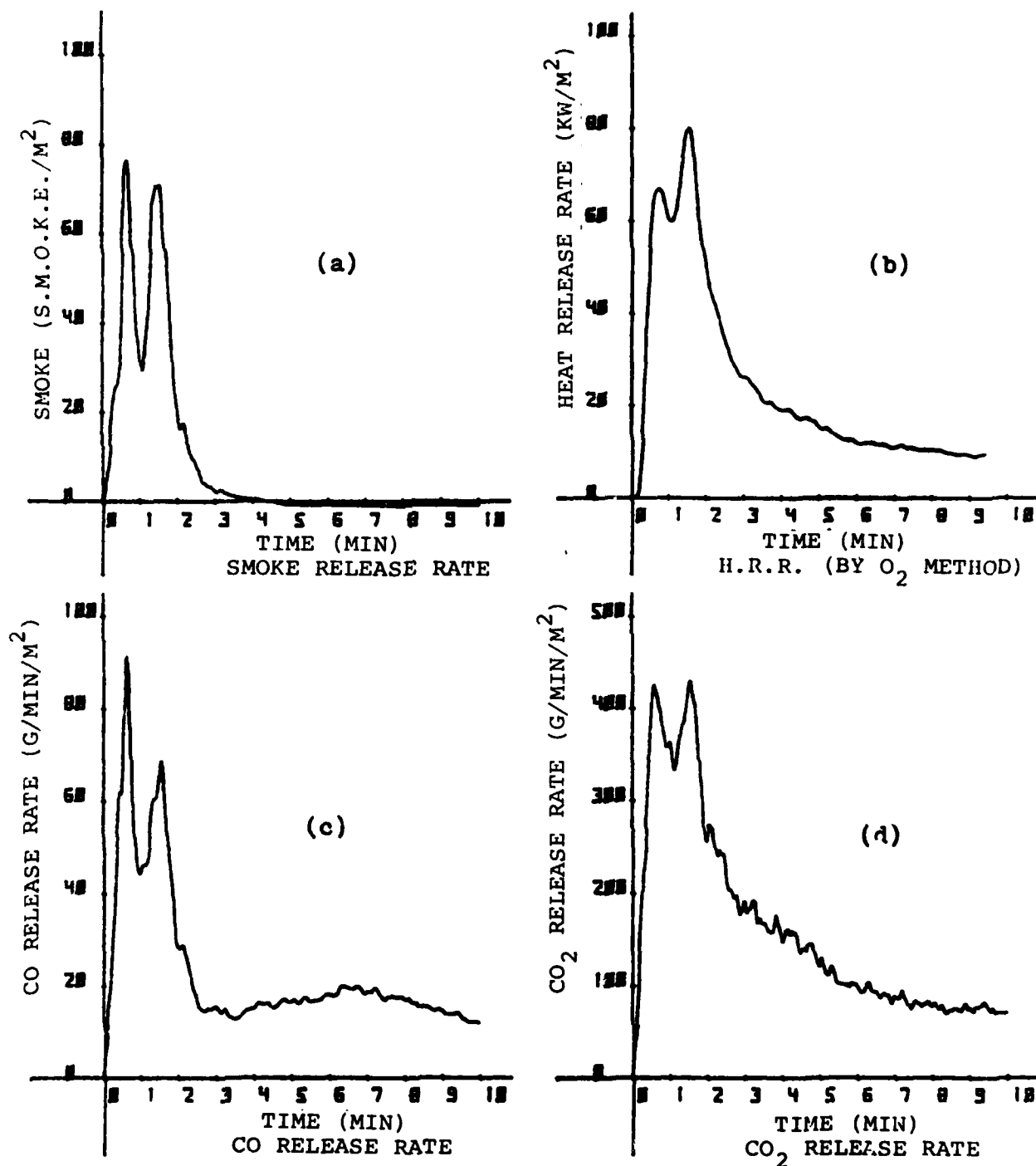


FIGURE 21. CHAS RELEASE RATE PROFILES--PANEL NO. 1 TEST AT 4.41 Btu/ft² SEC (5 W/cm²) (Sheet 1 of 3)

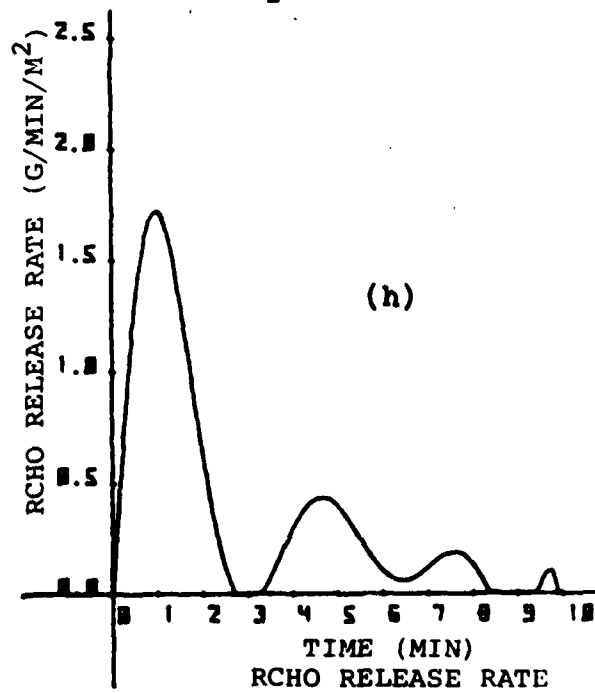
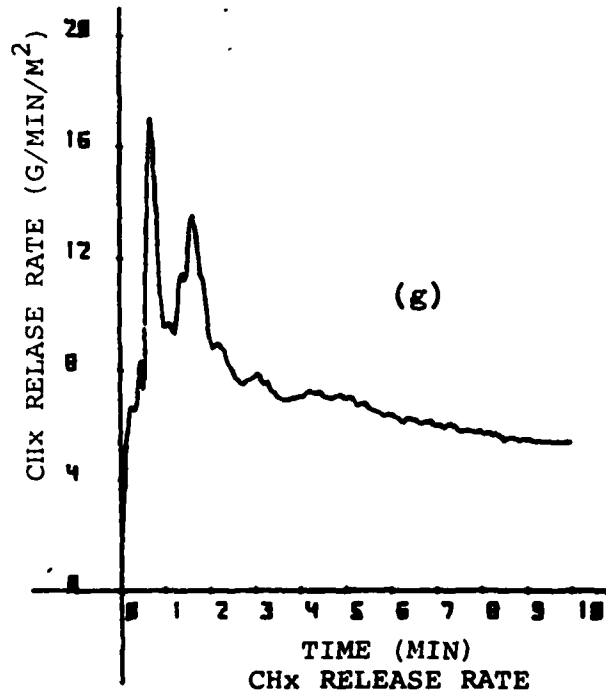
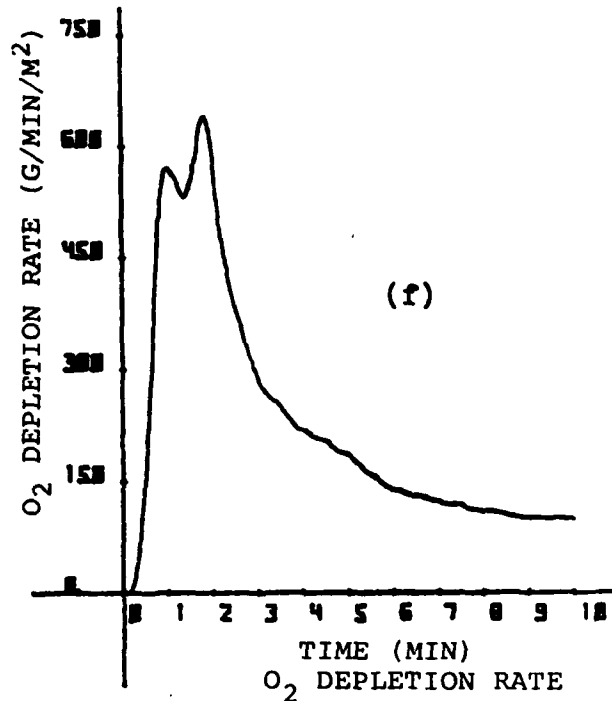
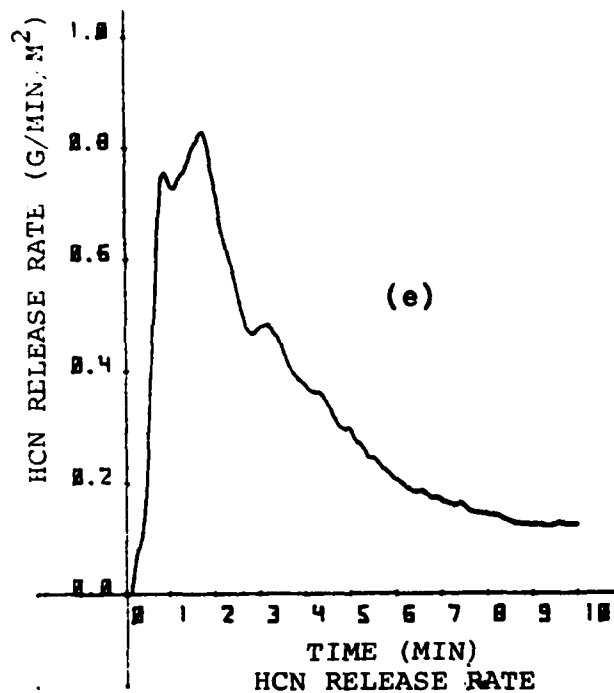


FIGURE 21. CHAS RELEASE RATE PROFILES--PANEL NO. 1 TEST AT 4.41 Btu/ft² SEC (5 W/cm²) (Sheet 2 of 3)

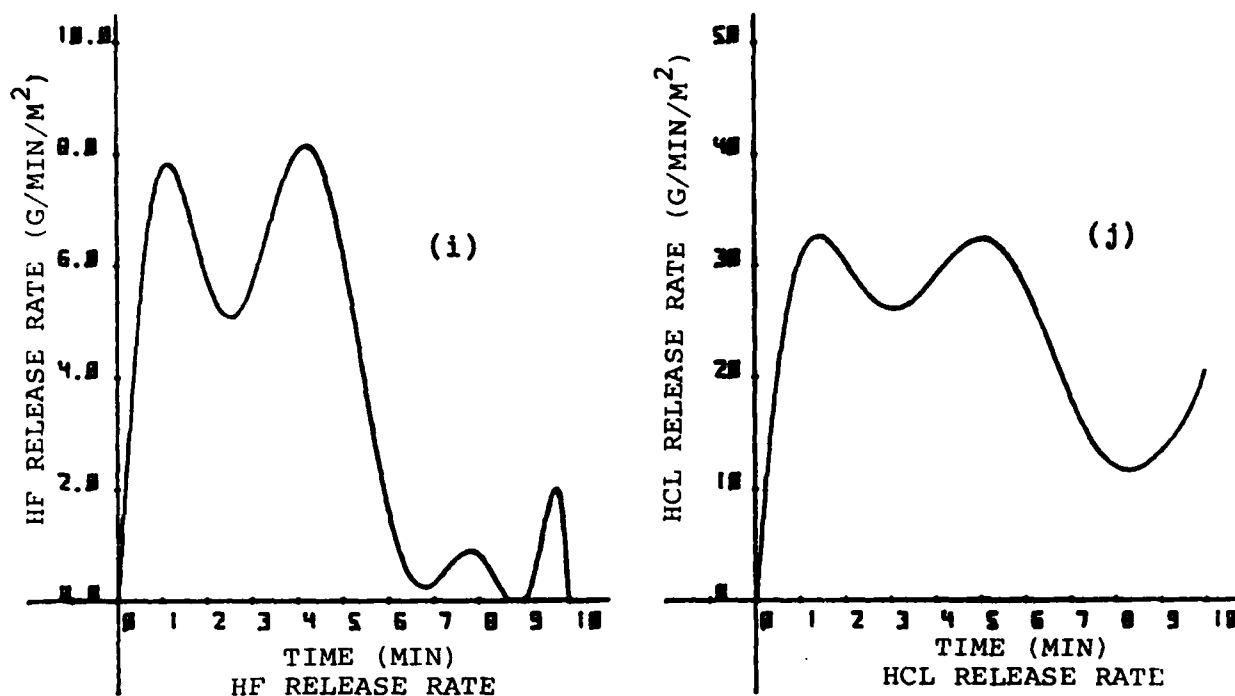


FIGURE 21. CHAS RELEASE RATE PROFILES--PANEL NO. 1 TEST AT 4.41 Btu/ft² SEC (5 W/cm²) (Sheet 3 of 3)

In general, the release rate profiles plotted for the ceiling test Panel No. 2 and the partition Panel No. 4 were very similar to those plotted for Panel No. 1. Two peaks in burning intensity accompanied by corresponding evolutions of smoke and gases were observed. Panels 2 and 4 also were honeycomb structures fabricated (with some variations in materials type and quantity) similar to Panel No. 1 (see Table 2). The burn profiles, therefore, were characterized by a rapidly developing major release rate peaks, followed in most cases by a second peak of lesser intensity as with panel 1. The peaks were delayed and spread out along the time axis when the test materials were run at lower heat fluxes (2.2 and 3.08 Btu/ft² sec).

Tables 5 contains the data from CHAS/SATS tests on panels 2, 3 and 4.

TABLE 5

SUMMARY OF EXPERIMENTAL CHAS/SATS DATA FOR CHI PROGRAM TEST
PANELS 2, 3 & 4

RUN NO. & DATE	SAMPLE NUMBER	HEAT FLUX W/cm ²	SAMPLE WEIGHT GRAMS	CHAR YIELD % C	HEAT RELEASE ①		S.M.O.K.E. RELEASE		TOTAL O ₂ DEPLETION IN 10 MIN GRAMS/m ²	TOTAL CO ₂ IN 10 MIN GRAMS/m ²	TOTAL CO IN 10 MIN GRAMS/m ²	TOTAL KCN IN 10 MIN GRAMS/m ²	TOTAL NO (NO _x) IN 10 MIN GRAMS/m ²	TOTAL (COMBUST. GAS-10 MIN GRAMS/m ²)	② ANIMAL T ₁ SEC	③ ANIMAL T _d SEC
					PEAK MAX kW/m ² (MIN)	TOTAL kW/m ² (MIN)	PEAK MAX SSU/m ² (MIN)	TOTAL SSU/m ² (MIN)								
10280 6-6-80	2-1-1	3.5	157.1	67.6	33 (0.75)	75	145 (0.45)	83	914	961	117	0.09	10	72	415	835
10380 6-9-80	2-1-2	3.5	155.5	68.8	34 (0.75)	76	147 (0.45)	101	-	964	126	-	7	86	700	1300
10480 6-9-80	2-1-3	3.5	156.7	65.8	34 (0.75)	52	150 (0.45)	87	988	1013	130	0.09	10	75	1075	1575
10580 6-10-80	2-1-4	2.5	156.6	75.3	75 (1.0)	57	86 (0.7)	63	577	589	82	0.04	4	47	1170	1700
10680 6-10-80	2-1-5	2.5	154.4	75.5	22 (0.9)	47	80 (0.93)	54	536	555	76	0.06	5	50	1460	2425-N ₂
10780 6-11-80	2-1-6	5.0	156.7	55.0	47 (0.4)	170	205 (0.3)	153	-	1441	240	0.12	10	119	490	1250
10880 6-11-80	2-1-7	5.0	154.5	44.6	48 (0.33)	179	211 (0.2)	165	1728	1669	300	0.10	11	140	365	865
10980 6-12-80	2-2-1	5.0	154.9	65.8	46 (0.45)	171	148 (0.3)	108	-	1182	170	0.13	8	91	585	750
11080 6-13-80	2-2-2	5.0	154.6	53.5	45 (0.50)	238	92 (0.3)	151	1388	1382	223	0.13	14	119	-	-
11180 6-16-80	3-1-3	3.5	388.2	16.1	115 (4.4)	500	87 (1.4)	257	-	3364	434	0.42	(13)	223	365	695
11280 6-16-80	3-1-2	3.5	146.1	14.4	128 (4.4)	652	84 (1.4)	229	5416	5155	544	0.56	(27)	324	-	-
11380 6-17-80	3-1-3	3.5	149.4	18.2	128 (3.5)	676	79 (0.85)	285	5576	5756	530	1.01	(29)	297	335	735
11480 6-17-80	3-1-4	3.5	150.0	18.3	138 (4.3)	646	161 (4.0)	326	5214	5264	589	0.27	22	333	-	-
11580 6-18-80	3-2-1	2.5	144.7	19.5	111 (6.5)	623	78 (6.0)	280	4467	4953	418	1.13	8	246	-	-
11680 6-18-80	3-2-2	2.5	143.0	23.9	98 (6.2)	591	63 (6.0)	272	4200	4833	322	1.0	(27)	239	985	1210
11780 6-19-80	3-2-3	2.5	143.9	19.7	100 (6.2)	578	75 (2.8)	207	3643	4248	312	0.79	(25)	236	1800	2060-N ₂
11880 6-19-80	3-3-1	5.0	147.5	19.3	151 (2.3)	633	133 (0.4)	437	5853	5539	661	1.71	25	410	-	-
12080 6-25-80	3-3-2	5.0	146.3	14.6	141 (2.3)	675	155 (1.35)	386	5312	8477	561	0.64	(25)	532	700	2050-N ₂
12180 6-25-80	3-3-3	5.0	147.5	8.5	143 (2.5)	697	175 (1.35)	448	4886	5098	516	1.40	(25)	386	270	535
12280 6-25-80	4-2-1	2.5	274.2	69.2	36 (1.25)	92	202 (0.93)	206	886	844	148	0.66	13	45	-	-

① Heat Release determined from thermopile.

② T₁ = Time to Incapacitation③ T_d = Time to Death

TABLE 5 (Cont'd)

S.F. NO. & DATE	SAMPLE NUMBER	HEAT FLUX W/CM ²	SAMPLE HEIGHT GRAMS	④ CHAP YIELD %	HEAT RELEASE 1		S.M.O.V.E. RELEASE			TOTAL O ₂ DEPLETION IN 10 MIN GRAMS/m ²	TOTAL CO ₂ IN 10 MIN GRAMS/m ²	TOTAL HCN IN 10 MIN GRAMS/m ²	TOTAL NO (NOx) IN 10 MIN GRAMS/m ²	TOTAL COMBUSTION GAS 10 MIN GRAMS/m ²	ANIMAL T ₁ SEC	ANIMAL T _d SEC
					PEAK MAX KW/m ² (MIN)	TOTAL 8 TO MIN KW/m ²	PEAK MAX SSU/m ² (MIN)	TOTAL 8 TO MIN SSU/m ²								
12380 6-26-80	4-2-2	2.5	MF	MF	41 (0.33)	125	212 (0.85)	225	1073	1074	176	0.48	(17)	175	540	1300
12490 6-26-80	4-2-3	2.5	MF	MF	37 (1.0)	132	209 (0.75)	249	1105	1117	188	0.21	(14)	163	445	1060
12500 6-26-80	4-1-1	3.5	266.7	50.7	42 (0.4)	136	229 (0.7)	358	1985	1763	368	0.50	20	295	-	-
12680 6-26-80	4-1-2	3.5	270.0	46.7	40 (0.7)	181	228 (0.5)	321	2053	2254	370	0.70	(21)	249	220	500
12780 6-27-80	4-1-3	3.5	266.8	51.6	37 (0.75)	157	228 (0.5)	307	2044	2465	362	0.66	(21)	271	138	258
12990 6-27-80	4-1-4	3.5	265.6	52.3	42 (2.2)	156	222 (0.55)	321	2213	1840	415	0.56	20	329	-	-
12980 6-30-80	4-3-2	5.0	268.2	46.7	49 (1.9)	226	275 (0.4)	292	1876	1696	345	0.67	(17)	268	80	300
13080 6-30-80	4-3-3	5.0	267.7	44.5	47 (1.9)	221	229 (0.4)	308	2048	1855	369	1.04	(18)	283	100	310
13180 6-30-80	4-3-1	5.0	267.4	45.2	50 (1.3)	232	233 (0.4)	320	2124	1834	367	0.42	18	317	-	-
13280 6-30-80	2-1-1	3.5	153.4	61.1	30 (0.75)	79	172 (0.4)	107	1023	1039	136	0.13	9	135	-	-
13380 7-1-80	4-1-2	3.5	267.4	51.0	36 (0.8)	152	227 (0.6)	294	1838	1588	339	0.47	18	237	-	-
13480 7-1-80	4-1-3	3.5	267.4	50.5	41 (2.5)	157	212 (0.7)	356	2007	2215	376	0.26	(18)	354	-	-
13580 7-1-80	2-2-2	2.5	157.6	29.9	26 (1.0)	68	124 (0.7)	79	720	704	103	0.12	(6)	99	-	-
13680 7-2-80	2-2-3	2.5	155.2	69.9	28 (1.0)	74	129 (0.7)	81	744	784	115	0.13	(7)	93	675	1180
13780 7-2-80	2-3-2	5.0	159.6	56.3	48 (0.6)	199	216 (0.3)	178	1337	1285	173	0.31	(10)	127	430	850
13880 7-2-80	2-3-1	5.0	158.4	54.5	47 (0.6)	190	216 (0.3)	172	1354	1281	166	0.10	10	146	1355	1650
13980 7-3-80	1-1-2	2.5	151.1	21.5	130 (4.5)	629	97 (4.7)	230	3843	4158	306	0.33	(23)	331	-	-

① MF = Instrument Malfunction

REPRODUCIBILITY- Figures 22, 23 and 24 show comparisons of the hazards release rate profiles for panels 2, 3 and 4 tested respectively at 4.41 Btu/ft² sec (5 W/cm²) radiant heat flux. All tests were run at constant airflow (60 ft³/min) using piloted ignition.

The release rate profiles for the 3 replicate tests of Panel No. 2 (Figure 22) show good reproducibility for smoke, heat, CO₂, and O₂ depletion. Greater deviation in response was shown in the plots for CO, particularly from 1 minute to 10 minutes. Two of the CO plots show that evolution began to increase slowly after 2 minutes whereas the CO₂ evolution was decreasing. This is symptomatic of smoldering. In the third test the CO decreased in the time frame from 2 to 10 minutes. Such disparities significantly indicate either a random burning pattern typical of composited structures (laminate over core layup) or are caused by variations in adhesive resin loadings from area to area during fabrication of a panel.

The HCN release rate plots showed the greatest variation. However, concentrations of HCN at these levels have little effect on the CHI measurements of these panels. In the majority of tests, as reflected by the data in Table 5, HCN production increased slightly at higher heat fluxes. It was noted that for those panels known to be fabricated from Nomex honeycomb core and epoxy adhesives (both containing nitrogen), 60 to 90 times more NO/NO_x was evolved than HCN.

Table 6 gives the average relative standard deviations (Av. RSD) for each of the fire response parameters measured in the triplicate runs plotted in Figures 22, 23, and 24 as listed in Table 5. While the Av. RSD is of little significance statistically, a simple evaluation of the relative precision of each of the parameters measured by the corresponding CHAS subsystem instruments can be made.

TABLE 6
AVERAGE RELATIVE STANDARD DEVIATIONS OF FIRE RESPONSE PARAMETERS MEASURED
IN REAL TIME BY THE CHAS *

PARAMETER	Yc	Pk HRR	10 min HR	Pk SMO	10 min SMO	O ₂	10 MINUTE TOTAL GAS YIELDS				
							CO ₂	CO	HCN	NO _x	CH _x
Av. RSD % Panel 2	11.8	3.7	14.6	6.2	8.2	14.5	13.8	27.6	61.1	18	8.2
Av. RSD % Panel 3	38.0	3.7	4.9	10.9	7.8	9.1	7.1	12.8	14.1	0.0	17.7
Av. RSD % Panel 4	2.4	3.1	2.4	1.8	4.6	6.3	4.8	3.7	43.9	3.3	8.7
Mean Av. RSD %	17.4	3.5	7.3	6.3	6.9	10.0	8.6	14.7	39.7	7.1	11.5

* = HEAT FLUX AT 4.41 Btu/ft² sec (5 W/cm²)

Yc = Char Yield, Av. RSD % for 3 Tests

Pk. HRR = Peak HRR value, Av. RSD % for 3 tests

Pk. SMO = Peak SMOKE values, Av. RSD % for 3 tests

10 min HR = Total heat release in 10 minutes, Av. RSD % for 3 tests

10 min SMO = Total SMOKE release in 10 minutes, Av. RSD % for 3 tests.

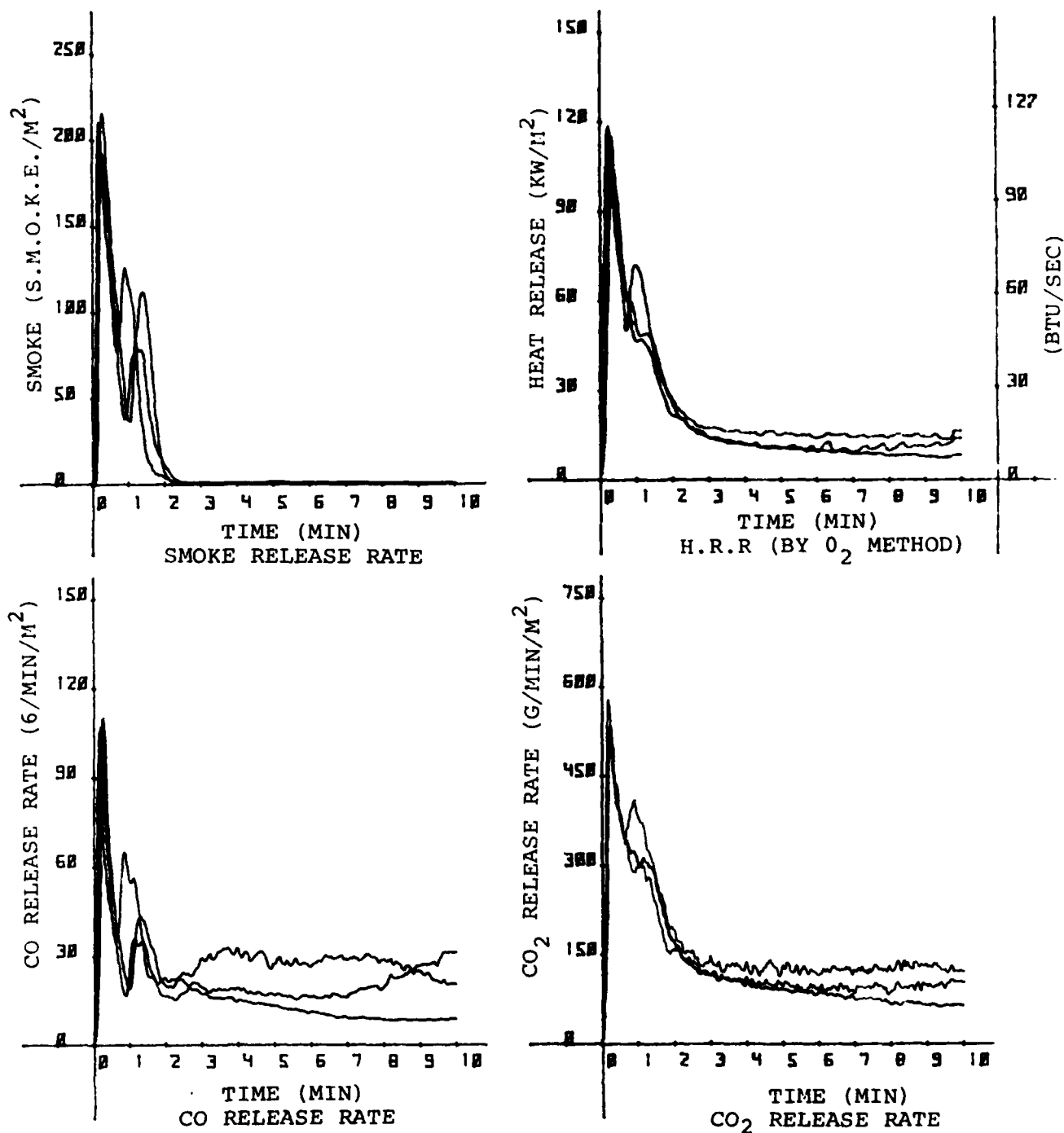


FIGURE 22. CHAS REPRODUCIBILITY OF HAZARDS RELEASE RATE--
CEILING PANEL NO. 2, 3 TESTS AT 4.41 Btu/ft² SEC
(5 W/cm²) (Sheet 1 of 2)

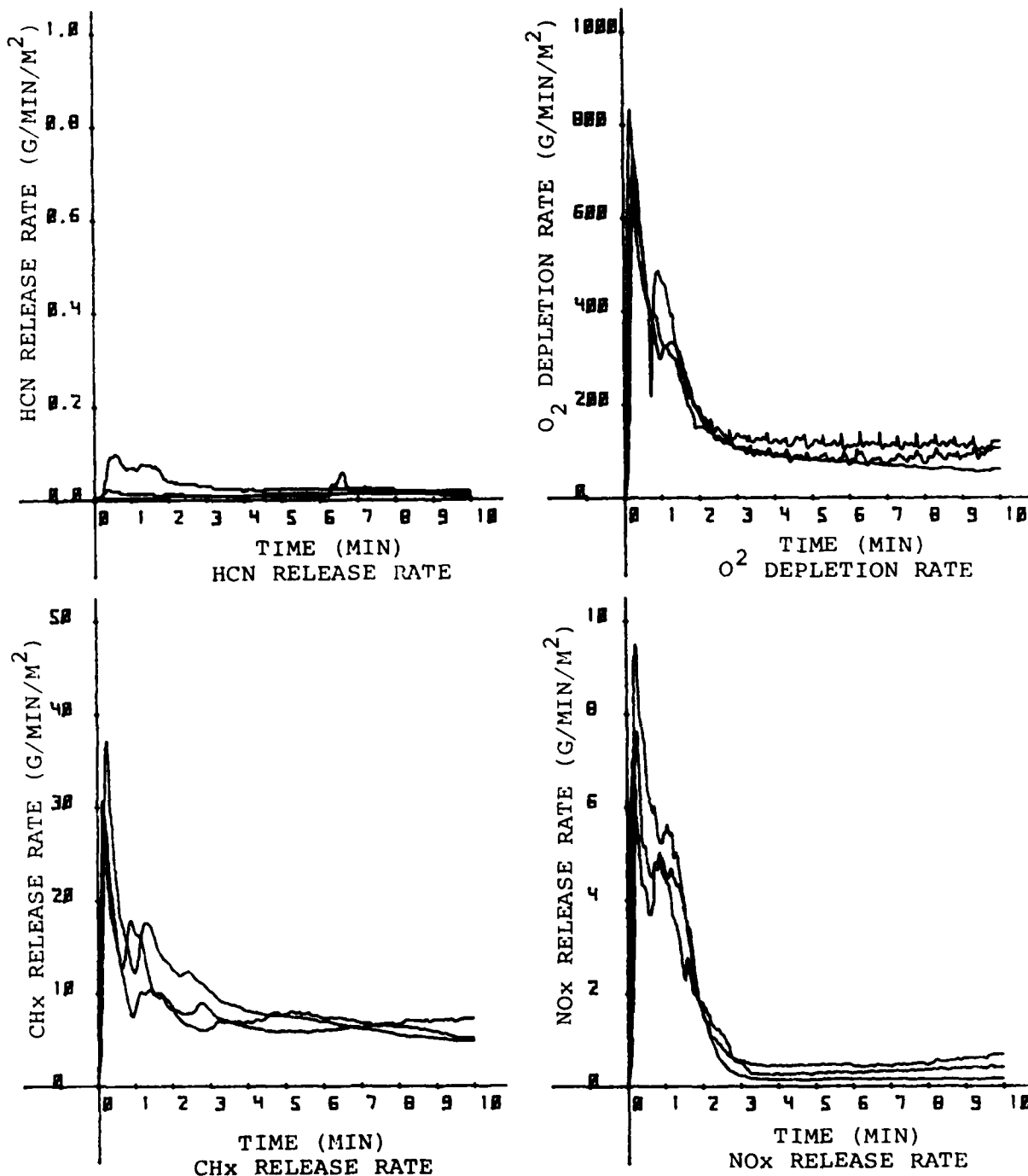


FIGURE 22. CHAS REPRODUCIBILITY OF HAZARDS RELEASE RATE--
CEILING PANEL NO. 2, 3 TESTS AT 4.41 Btu/ft² SEC
(5 W/cm²) (Sheet 2 of 2)

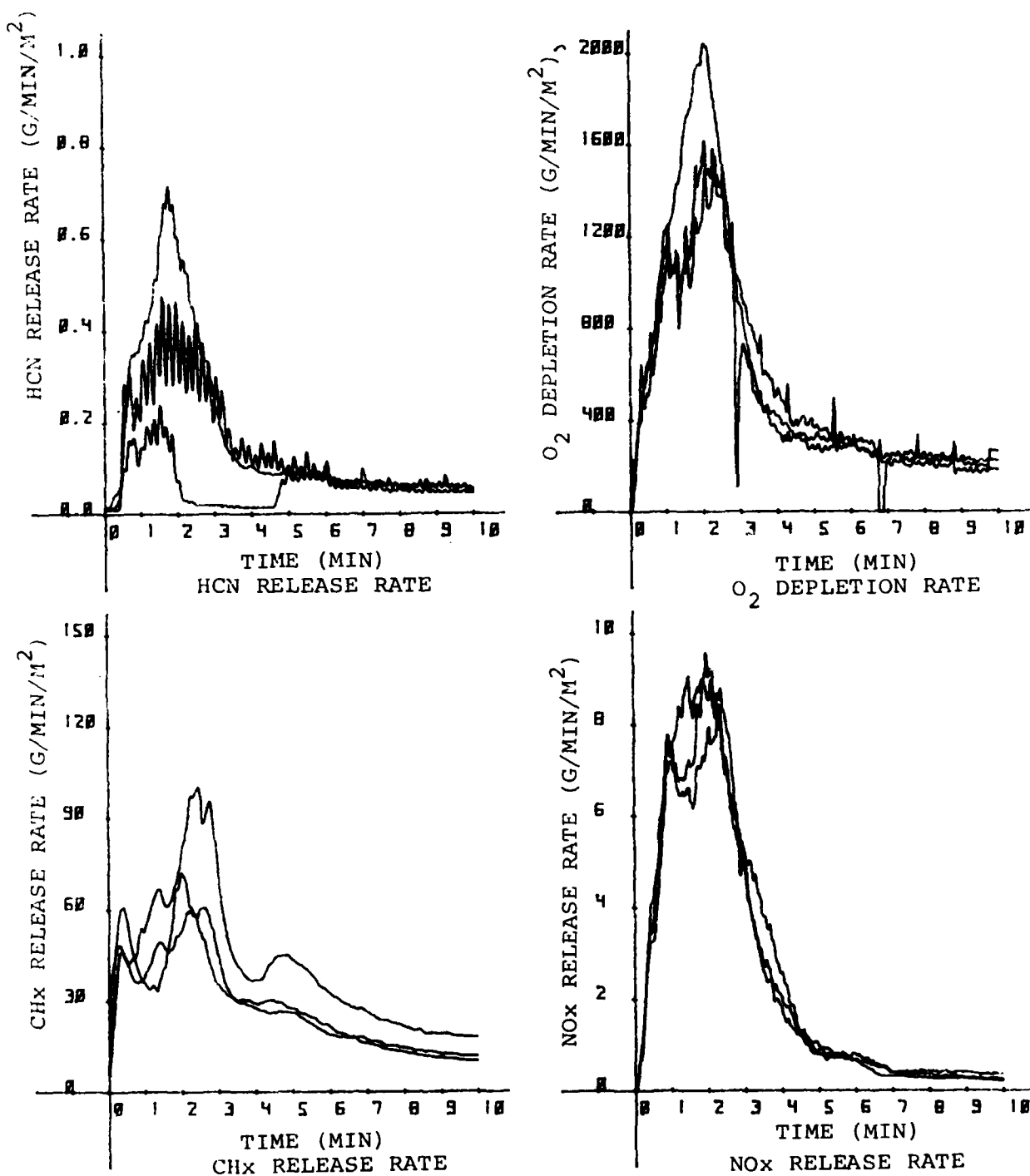


FIGURE 23. CHAS REPRODUCIBILITY OF HAZARDS RELEASE RATES--
POPLAR WOOD FACED PANEL NO. 3, 3 TESTS AT 4.41 Btu/ft²
SEC (5 W/cm²) (Sheet 1 of 2)

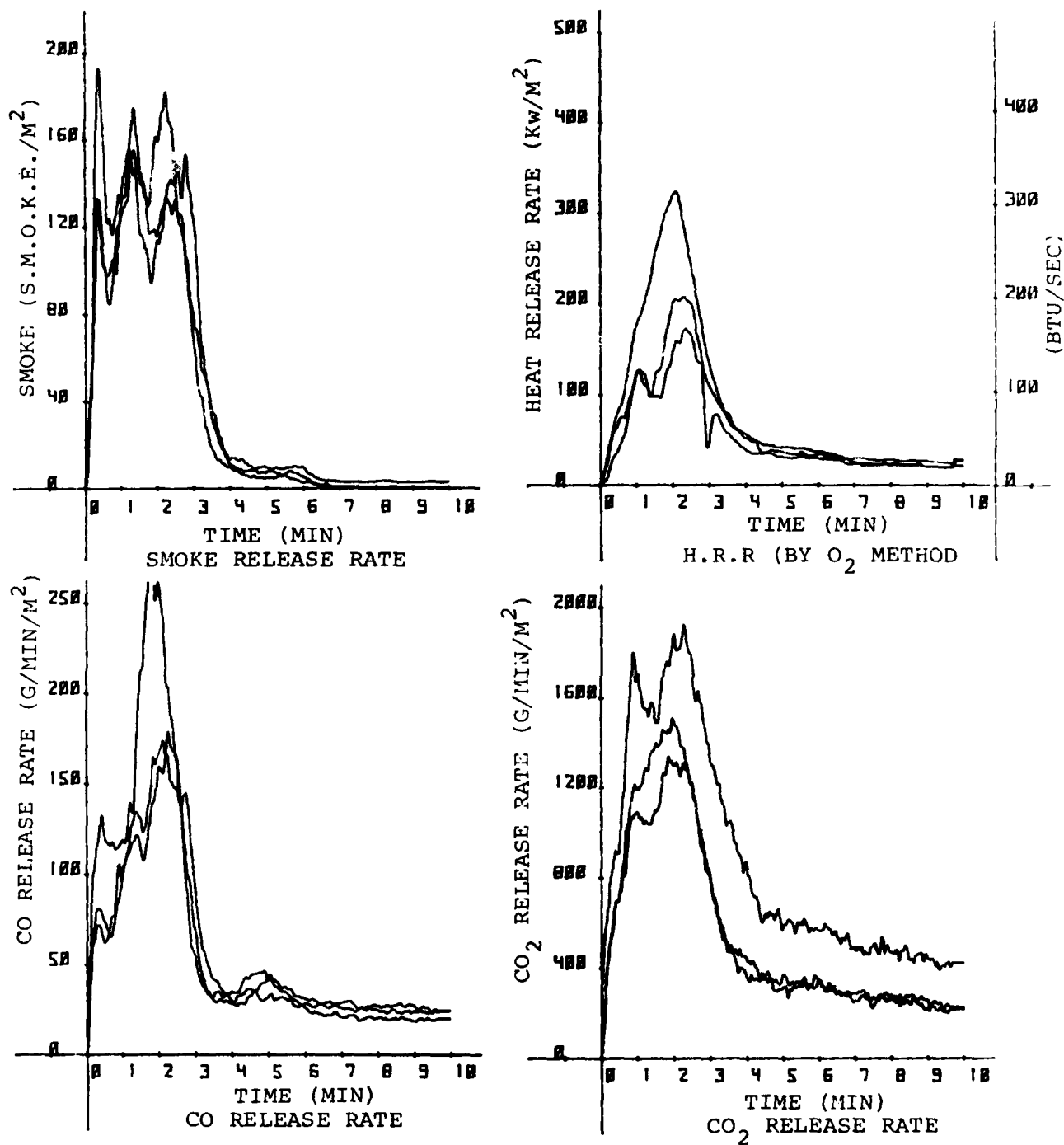


FIGURE 23. CHAS REPRODUCIBILITY OF HAZARDS RELEASE RATES--
POPLAR WOOD₂FACED PANEL NO. 3, 3 TESTS AT 4.41 Btu/ft²
SEC (5 W/cm²) (Sheet 2 of 2)

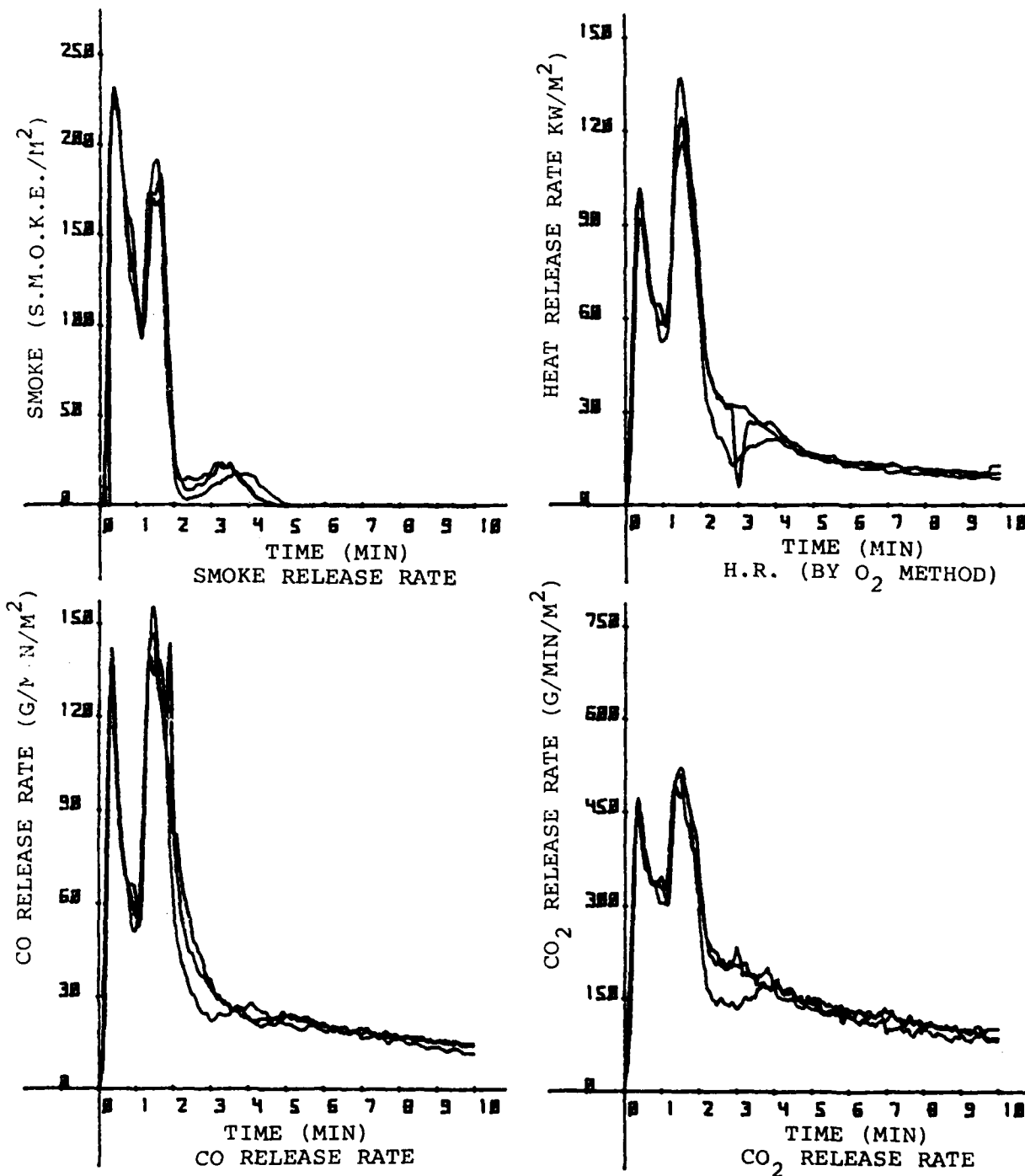


FIGURE 24. CHAS REPRODUCIBILITY OF HAZARDS RELEASE RATE-₂
 PARTITION PANEL NO. 4, 3 TESTS AT 4.41 Btu/ft²
 SEC (5 W/cm²) (Sheet 1 of 2)

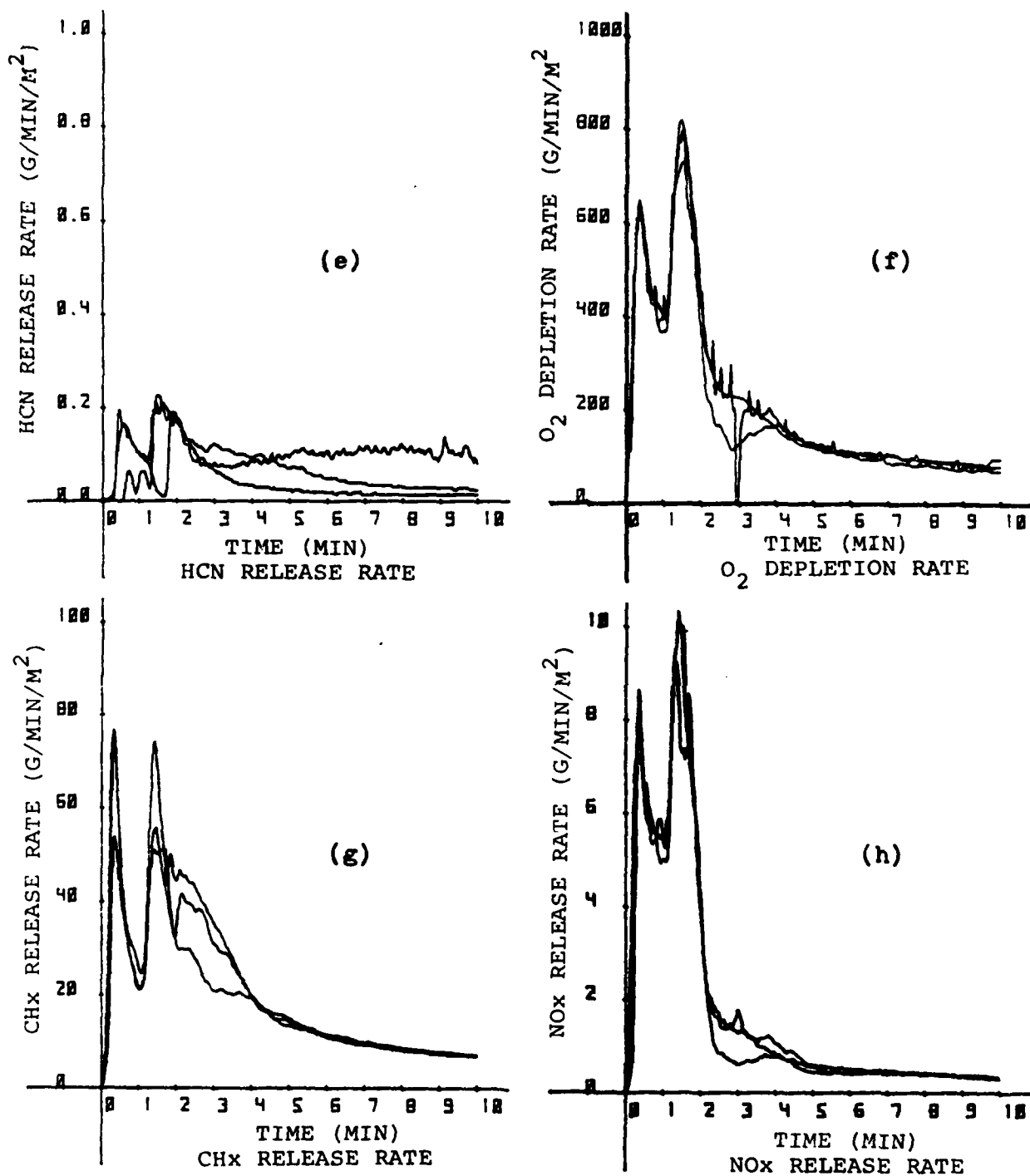


FIGURE 24. CHAS REPRODUCIBILITY OF HAZARDS RELEASE RATE-2
PARTITION PANEL NO. 4, 3 TESTS AT 4.41 Btu/ft²
SEC (5 W/cm²) (Sheet 2 of 2)

The peak heat release rate (measured by the DTP) was the most reproducibly measured parameter in the CHAS as reflected by the 3.5% mean Av. RSD. Total (10 minute) heat release Av RSD's ranged from 2.4 to 14.6% with a mean Av. RSD of 7.3%. Smoke was measured with the next best precision with a range of 1.8 to 10.9%; a mean Av. RSD of 6.3% for peak reproducibility, and a mean Av. RSD of 6.9% for total (10 min) smoke (range, 4.6 to 8.2%). Of the gases, NO/NOx was measured with the best precision (7.1% mean Av. RSD). However, the range of the NO/NOx Av. RSD's was higher than for CO₂, which showed a mean Av. RSD slightly higher but narrower in range. CO and HCN were the least reproducible of the measurements included in this evaluation. The mean Av. RSD for CO was biased toward a higher value by the 27.6 Av RSD% obtained from the 3 test runs selected for comparison in the plots of Figure 22(c). The variance was accentuated also in this case by integration of the area under the curves. The range in Av. RSD's would have been less if random burning had not occurred and were therefore not a true measure of instrument precision or accuracy. The mean Av. RSD for HCN (39.6%) is misleading because the HCN monitor sampling system was found to leak air into the detector after all tests had been completed. The larger than expected Av. RSD for the char yield, Yc, for Panel No. 3 was caused by loss of weight due to spalling of ash and char material into the bottom of the HRR chamber during a test. More accurate mass loss measurements relating to smoke and gases can be obtained if a catch pan is installed at the bottom of the sample holder.

The Av. RSD's listed in Table 6 and the replicate plots of the hazards shown in Figures 22-24 illustrate the degree of reproducibility attainable under ideal test conditions. These tests were made on the same day using improved procedures resulting from experience gained from previous tests. Panel 4 was uniform in construction and appeared to reflect this characteristic in the replicate burn tests. This was evident from the Av. RSD's (Table 6) which were much lower than those listed for earlier tests of the other panel materials.

For materials that characteristically burn uniformly, and with all CHAS systems accurately calibrated, the measurements for most of the hazards monitored in real time will probably agree within 2-9% RSD's for repeat tests. This is somewhat better than the precision specified for heat and smoke (12.5%) in the current draft of the proposed standard test procedure (reference 7) used for the OSU Rate of Heat Release Calorimeter.

Estimates of the reproducibility of the measurements for HF, HCl, and aliphatic aldehydes were more difficult to calculate than for the gases monitored in real time. Only approximations of the actual release rate profiles for each gas could be plotted using only the 10 syringe samples taken during a 10 minute test. Instantaneous concentrations were not measured at other times which left voids in the data. Reproducibility of these measurements are affected also by the accuracies of taking the 45 ml gas sample at each time interval; deviations in the uniformity of cutting the samples to 10 x 10 or 6 x 6 inch sizes; the accuracy of measuring the 5 ml absorption solution loaded into each syringe; the accuracy and constancy of the HRR airflow settings; and the detectability limits and accuracies of the microchemical analyses performed for each gas.

The selective ion electrode method used for the fluoride determinations is specific for hydrolyzable fluoride and has a lower limit of detectability of 0.01 ppm. At this limit of detection, the corresponding release rates in terms of grams of HF per minute per m² (10.76 ft²) were 0.008 or 0.02 when 10 x 10 or 6 x 6 inch samples, respectively, were tested. The spectrophotometric method for determination of aliphatic aldehydes is capable of detecting 0.007 and 0.02 g/min/m² release rates from tests made on the 10 x 10 and 6 x 6 inch samples. The lower detection limits for the silver nitrate titrametric method used for HCl determination for these sample sizes was 0.75 and 2.0 g/min/m².

Based on the above detection limits for HCl, HF and aliphatic aldehydes, it is apparent that reproducibility of results from run to run on the same material are affected to a much greater extent by sampling errors.

Calculations showed that an error of 0.1 ml in measuring the absorption solution into a syringe would cause a relative error of 2.0% in the final result (g/min/m²). Additional calculations for other sampling errors indicated the following:

+ 1.0 ml error in gas volume (by syringe) = +2.27% error (45 ml. gas sample)

+ 0.5 ft³/min HRR airflow rate adjustment = +0.83% error (at 60 ft³/min)

+ 1/16" inch dimensional error in cutting the sample (10 x 10 inch sample) = +1.27 % error

Two of the possible sampling deviations are directly proportional to the calculated g/min/m². The remaining two are inversely proportional and could partially cancel each other in the final calculation of the release rate.

If each of the errors occur at the maximum probable limits for the four sources of error listed above and act in the same direction, the maximum error would add up to + 6.4%. Other systemic errors affecting the concentration determinations for these active gases, i.e., variations in heat flux or system absorptive effects, are not easily evaluated. The estimated combined relative error, taking into account an estimated coefficient of variation for the microchemical methods of 2 times the detectability limit for each gas gave total relative probable errors as shown in Table 7.

TABLE 7

ESTIMATED PROBABLE RELATIVE ERRORS FOR THE DETERMINATION OF HF, HCl
AND ALIPHATIC ALDEHYDES BY THE CHAS SYRINGE METHOD OF ANALYSIS

	PROBABLE RELATIVE ERROR IN g/min/m ² FOR SAMPLES (ROUNDED VALUES)	
<u>GAS</u>	<u>10 X 10 IN</u>	<u>6 X 6 IN</u>
Aliphatic Aldehyde (RCHO)	± 6%	± 7%
HF	± 6%	± 7%
HCl	±13%	±27%

The computer plots of the HF, HCl, and RCHO release rate profiles shown in Figures 25 through 31 illustrate a reasonable degree of reproducibility between panel samples of the same material if the assumption of uniform burning is made. For example, Figure 25 shows plots of the RCHO release rate profiles for two runs of the ceiling panel No. 2 at 2.08 Btu/ft² sec (2.5 W/cm²) flux. In this case, the syringe samples were taken at the same time intervals. Since the one zone and 20 zone FACP's required an input of the quantities of RCHO released over each interval of time, the area under the profile over each time interval was used. This was an approximation since the release rate data at other time intervals was not known, even though the apparent total release of RCHO calculated from the profiles in Figure 25 were identical after 10 minutes (2.3 g/min/m²).

Figure 26, which shows two RCHO release rate profiles for panel No. 4 tested at 4.41 Btu/ft² sec (5 W/cm²), illustrates very well the difficulty of using single plots to obtain the quantitative data needed for the FACP. Staggered time interval syringe gas samples were taken on these two runs (Figure 26), at 15 sec intervals instead of 30 second intervals for the first 2 1/2 minutes. From this plot it was evident that the 1st peak evolutions at 0.52 g/min/m² was missed in run 12980. The profile of run 13080 indicated that a large peak release occurred at 2.25 minutes which was entirely missing in run 12980. The total RCHO calculated by the integration method showed a 0.7 g/ml difference in the 10 minute release. The data plotted for the two profiles in Figure 26 were combined for in Figure 27 for input via the Dylon formatter to the IBM 370 tape for use in the FACP programs and calculation of the CHI. In this run the 10 minute release was 1.2 g/m².

Similar examples of plots for HCl are shown in Figures 28 and 29, and in Figures 30 and 31 for HF release rates obtained from tests on panel 4 at 4.41 Btu/ft² sec (5 W/cm²) in the CHAS.

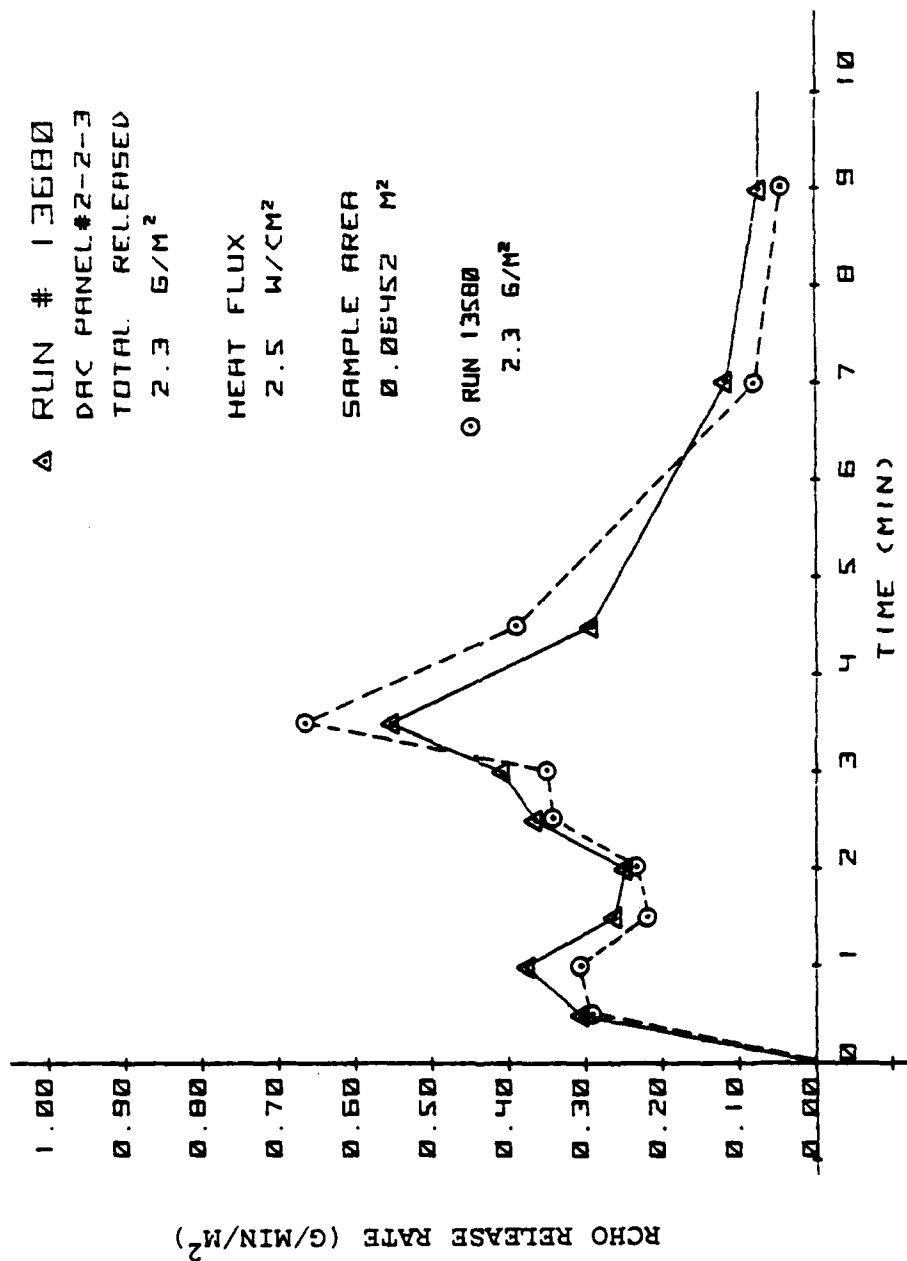


FIGURE 25. COMPARISON OF ALIPHATIC ALDEHYDE RELEASE RATES FOR TWO TESTS OF PANEL 2 AT 2.2 Btu/ft² SEC (SAMPLED AT SAME TIME INTERVALS)

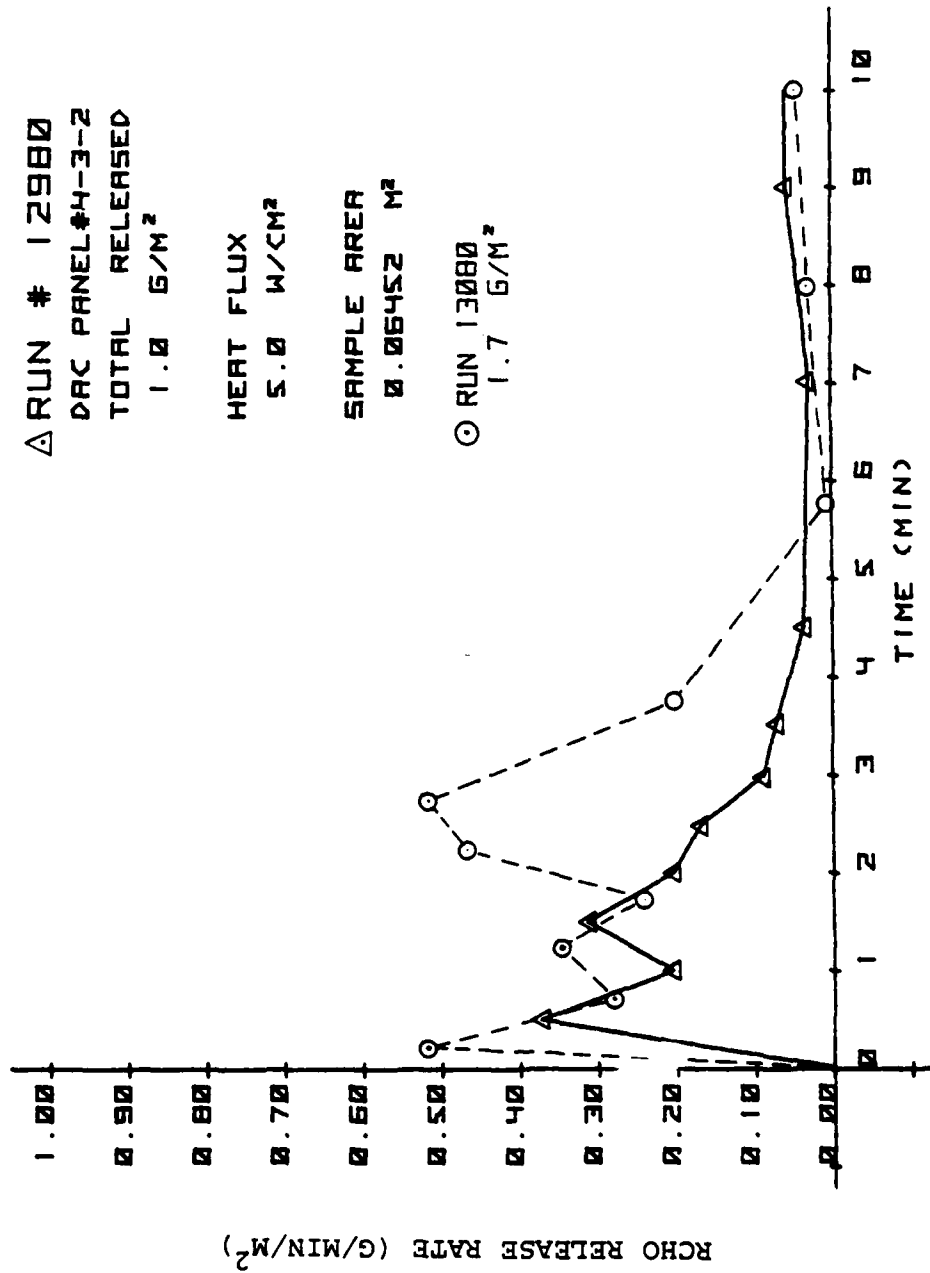


FIGURE 26 ALIPHATIC ALDEHYDE RELEASE RATES FOR TWO TESTS
 OF PANEL 4 AT 4.41 Btu/ft² sec (AT DIFFERENT
 TIME INTERVALS)

RUN # 13080
DAC PANEL#4-3-3
TOTAL RELEASED
1.2 G/M²

HEAT FLUX
5.0 W/CM²

SAMPLE AREA
0.06452 M²

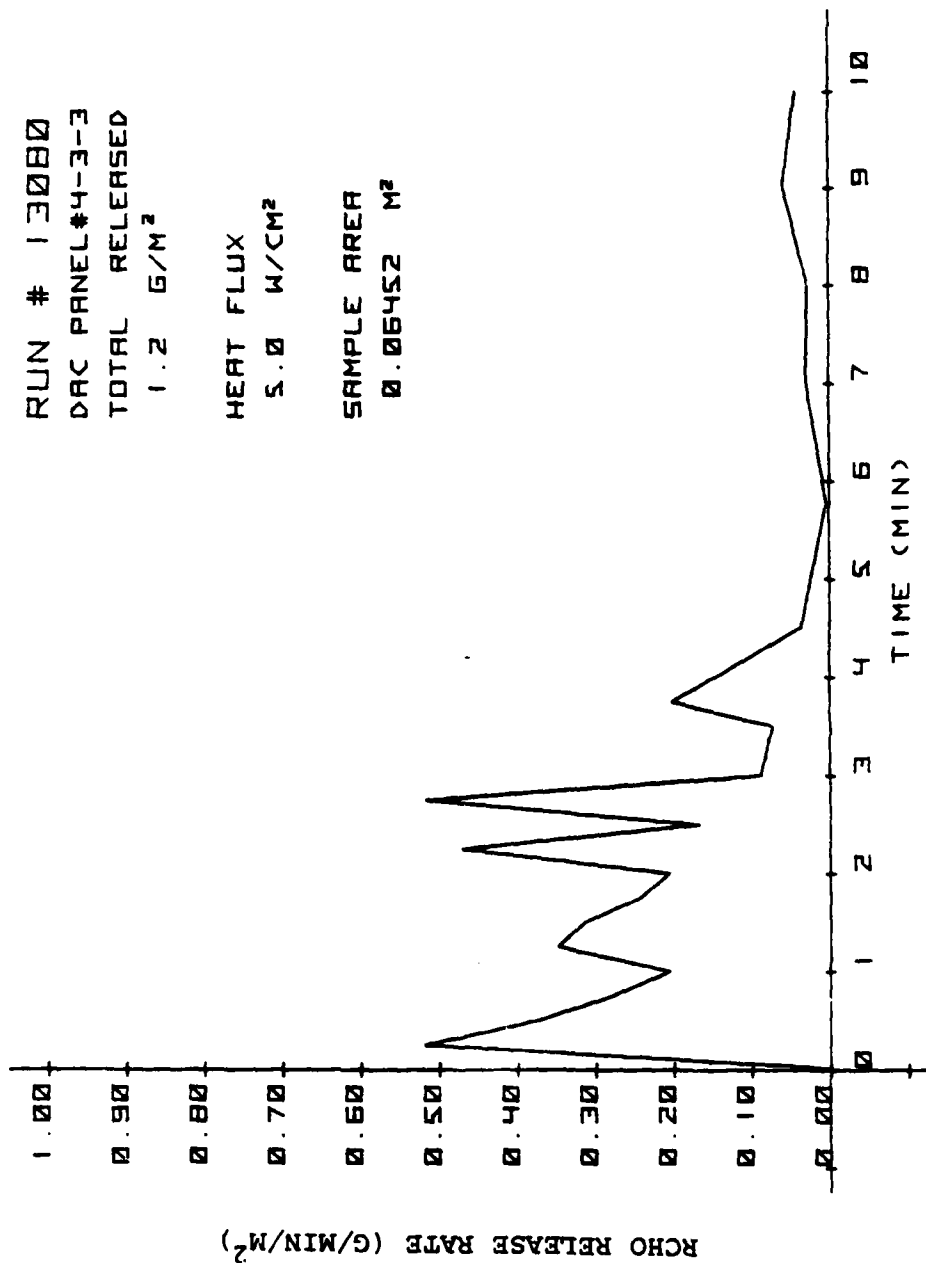


FIGURE 27 ALIPHATIC ALDEHYDE RELEASE RATE COMPOSITED FROM
PANEL 4 TESTS (FIGURE 26)

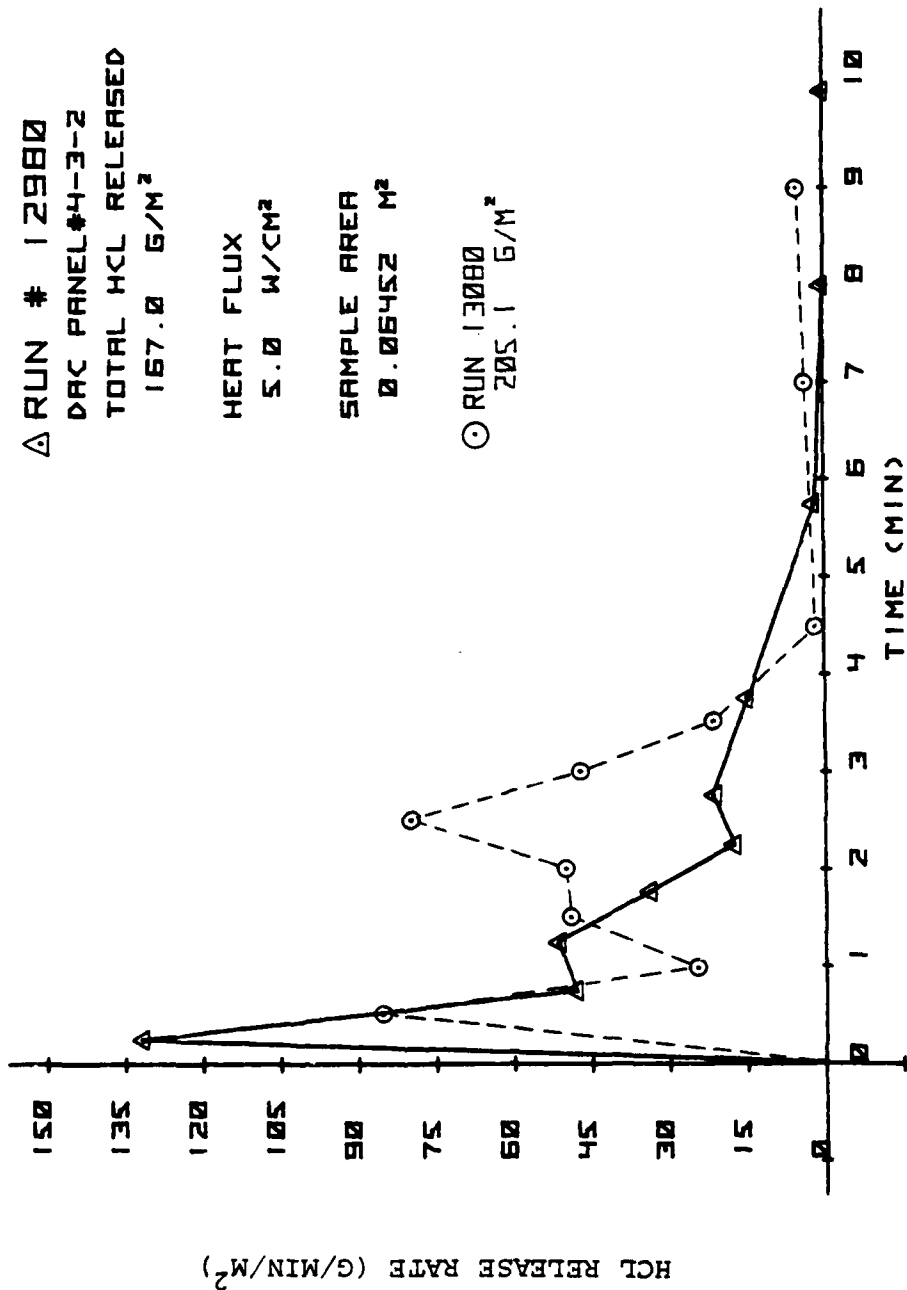


FIGURE 28. HYDROGEN CHLORIDE RELEASE RATES FOR TWO TESTS OF
 PANEL 4 AT 4.41 Btu/ft² SEC (AT DIFFERENT TIME
 INTERVALS)

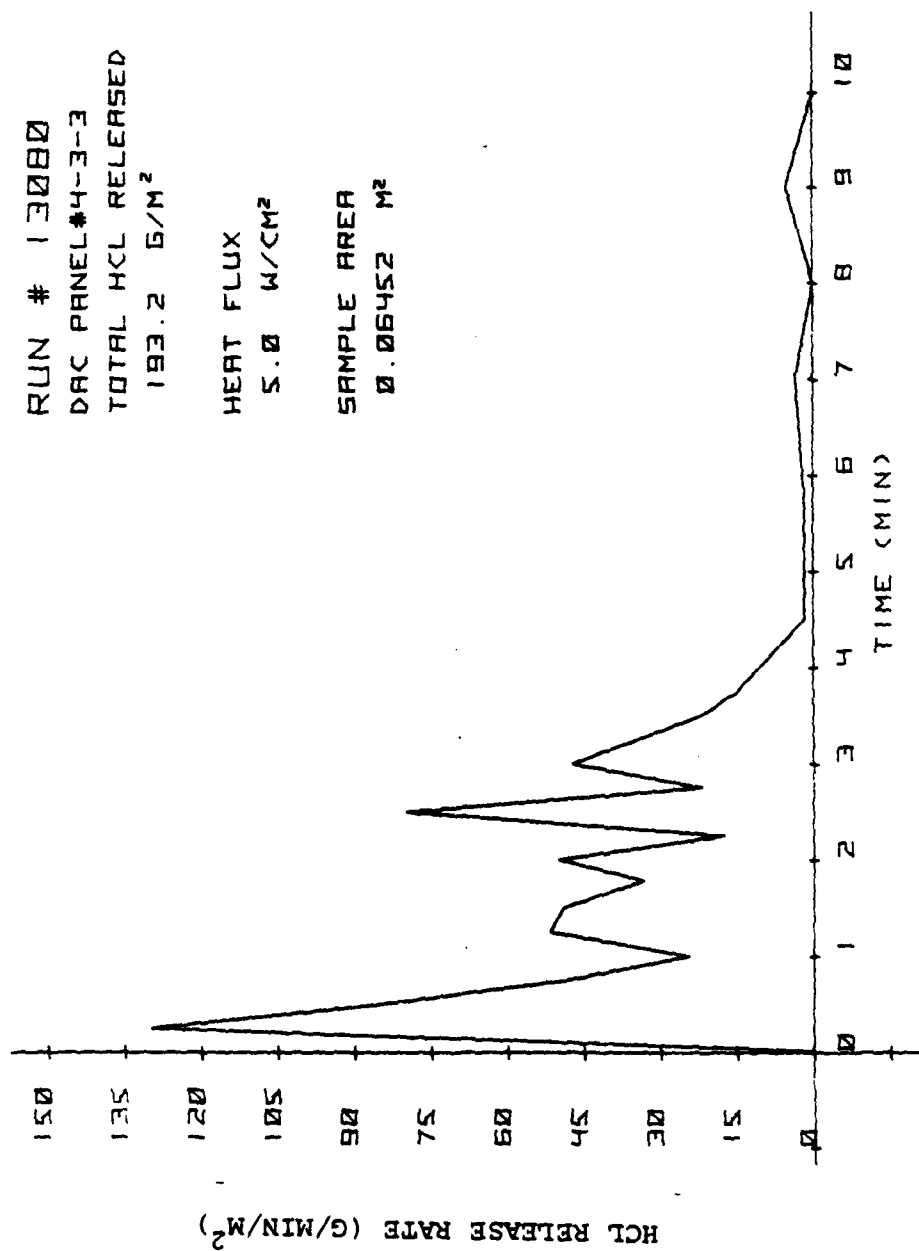


FIGURE 29. HYDROGEN CHLORIDE RELEASE RATE COMPOSITED FROM
PANEL 4 TESTS (FIGURE 28)

Δ RUN # 12980
 DAC PANEL #4-3-2
 TOTAL HF RELEASED
 41.7 G/M²

HEAT FLUX
 5.0 W/CM²

SAMPLE AREA
 0.06452 M²

○ RUN 13080
 61.8 G/M²

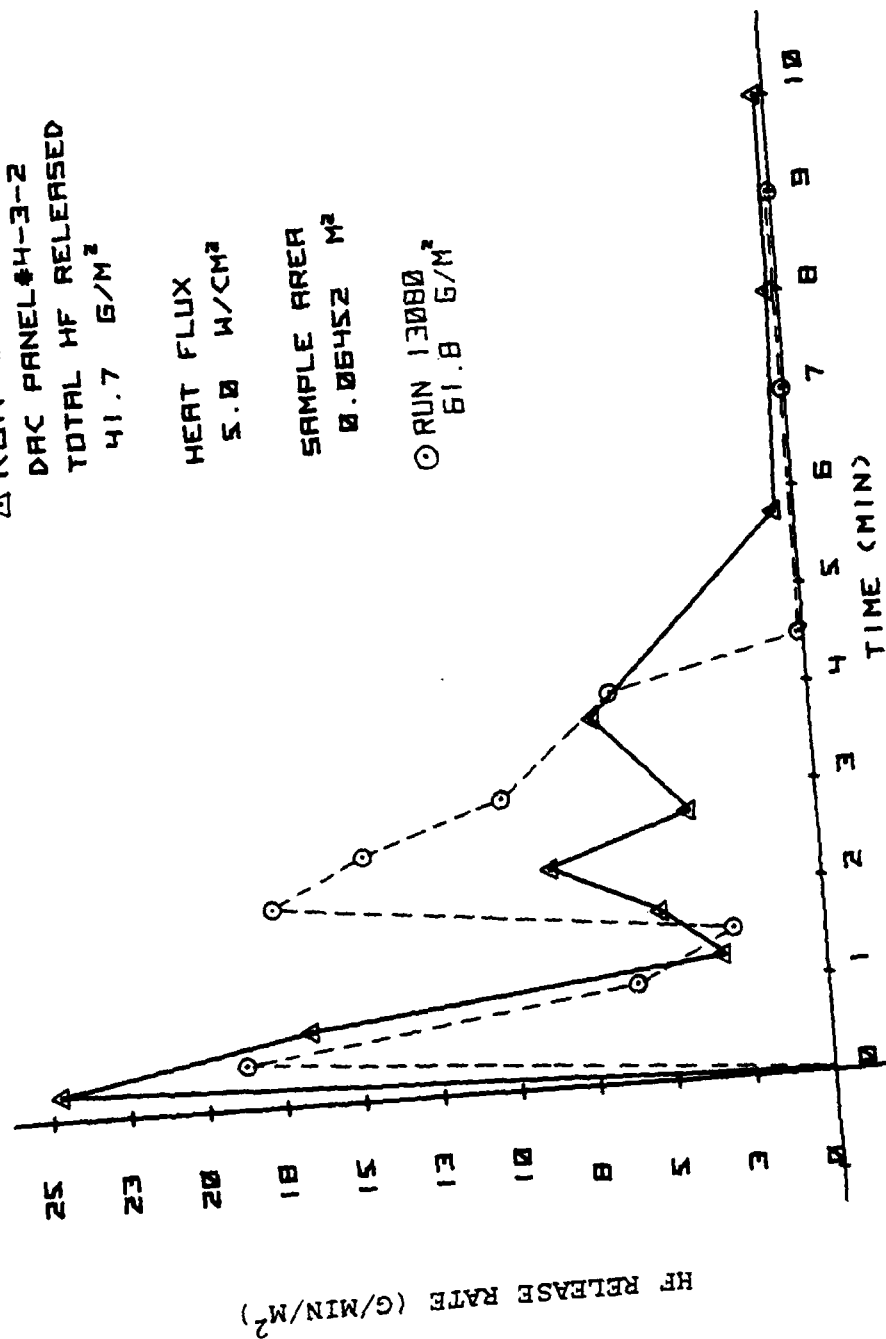


FIGURE 30. HYDROGEN FLUORIDE RELEASE RATES FOR TWO TESTS OF
 PANEL 4 AT 4.41 BTU/FT² SEC (AT DIFFERENT TIME
 INTERVALS)

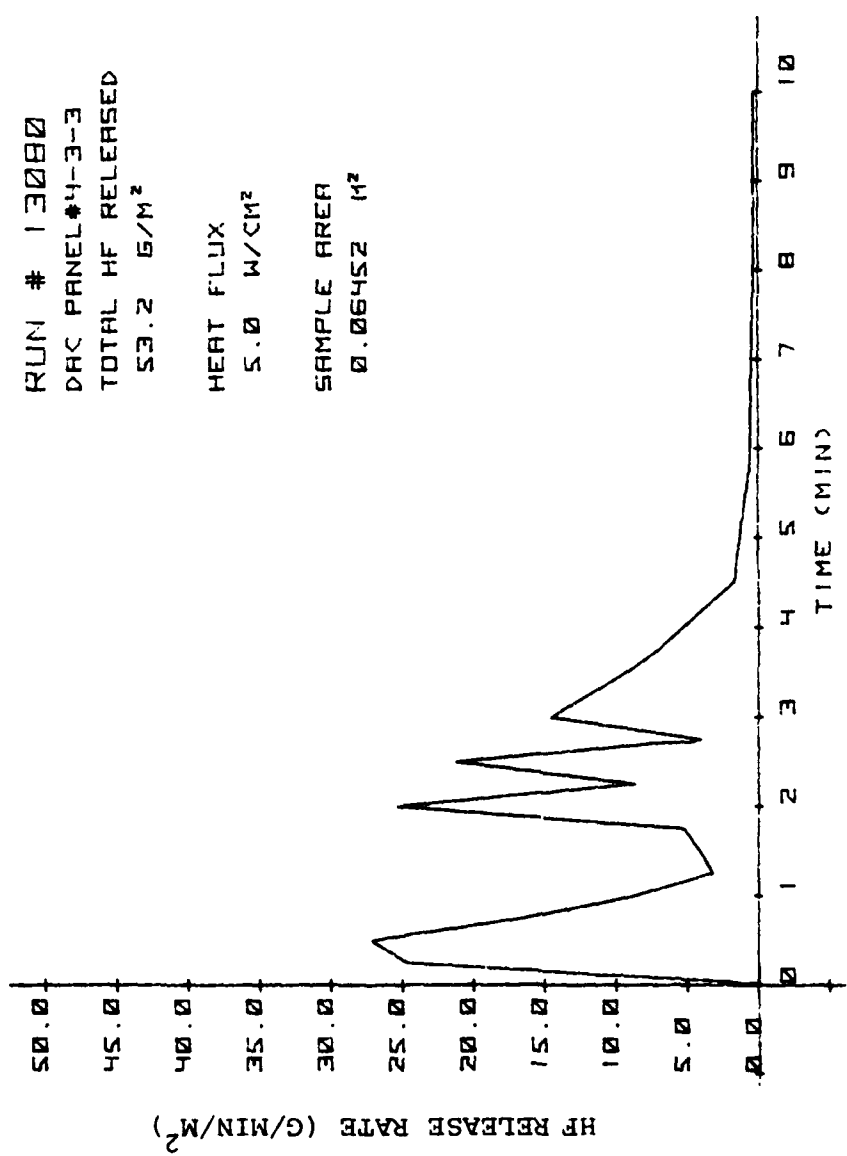


FIGURE 31. HYDROGEN FLUORIDE RELEASE RATE COMPOSITED FROM
PANEL 4 TESTS (FIGURE 30)

The HF, HCl and RCHO release rate data for panels 2, 3 and 4 are summarized in Table 8. The peak release rate maximum values shown in the table are comparable only for duplicate runs where syringe sampling sequences were identical (E,E; C,C; or B,B). The plots of release rates (Figures 26 through 31) show that comparisons of peak values to judge reproducibility are not valid even when only a 15 second difference in syringe sampling was used. Release rates of these gases appear to change rapidly during the burn tests in many instances. In general, the release rate profiles show 2 or more peaks at time intervals consistent with the other hazards and with the successive burning of the front and back sides of a specimen. At higher heat flux exposures, the release rate of products evolved from the front surface layers flashes off very rapidly. This is apparent with the HF evolutions at 4.41 Btu/ft² sec (5 W/cm²) flux observed for three runs of panel No. 2 (10780, 10880, and 13780). The syringe samples in the first two runs were taken after the peak evolution of HF had occurred.

Considering all of the possible sources of error in the CHAS/SATS hazards release data, two factors appeared to affect the reproducibility of replicate test data as much or more than the inherent errors associated with the individual methods of analysis used. The release rate data and the plots of the hazards indicated that variations in composition (distribution of components) in panel fabrication and random burning were important additional factors affecting reproducibility.

VARIATION OF HAZARDS RELEASE RATES WITH HEAT FLUX- Variations in the hazards released by panels 2, 3, and 4 at 2.2, 3.08, and 4.41 Btu/ft² sec heat flux were plotted for comparisons in Figures 32, 33 and 34. A casual inspection of these profiles showed the expected increase in release rates of hazards at higher radiant heat flux exposures. Closer examination revealed a uniform shift of the burn sequences, reflected by the peaks and valleys shown for each profile, toward shorter time intervals. This time compression of the hazards release rate peaks indicated that flaming of the back surface of a test specimen usually occurred earlier in a test following front surface flame involvement at higher heat flux test levels. This behavior was observed mainly when comparing 3.08 to 4.41 Btu/ft² sec runs. The second peak, indicating extensive back surface flaming, was not observed with panel 2 when tested at 2.2 Btu/ft² sec. This was probably due to the higher decomposition temperature of the back face material and the absence of less temperature resistant decorative layers. Panels 3 and 4, which were fabricated with decorative layers on both sides, showed multiple peaks, even at the lower heat flux test level.

In addition to time compression of the hazard release rate peaks, the profiles shown for these panels in Figures 32, 33 and 34 also show that most of the hazards release rates increase with heat flux. Aliphatic aldehydes (RCHO), and HCN appeared to deviate from this behavior to some degree. Since materials tested under the prescribed airflow rates in the CHAS never experienced an oxygen starved environment, increased heat fluxes (higher sample temperatures) favor oxidation. Thus higher heat fluxes favor conversion of HCN to N₂ and CO to CO₂ when excess oxygen is available.

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A COMBINED HAZARD INDEX FIRE TEST METHODOLOGY FOR AIRCRAFT CABI--ETC(U)

APR 82 H H SPIETH, J G GAUME, R E LUOTO

DOT-FA77WA-4019

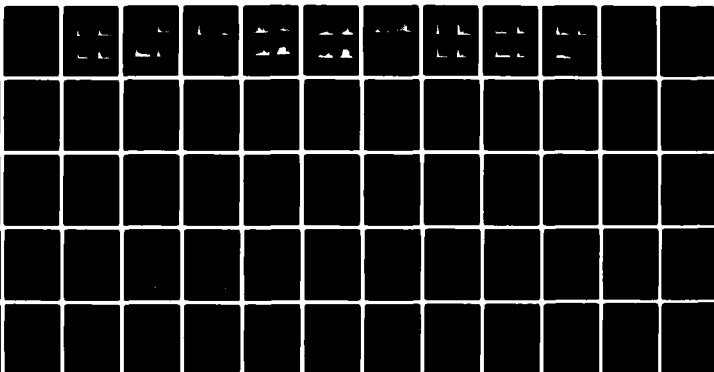
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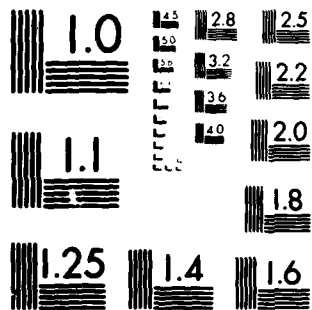
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TABLE 8
RELEASE RATES OF ALIPHATIC ALDEHYDES, HF AND HCl FROM TEST PANELS 2, 3, AND 4

RUN NO.	SAMPLE NO.	HEAT FLUX	ALIPHATIC ALDEHYDES		HF		HCl	
			PEAK () = MIN g/min/m ²	TOTAL-10 MIN g/m ²	PEAK () = MIN g/min/m ²	TOTAL-10 MIN g/m ²	PEAK () = MIN g/min/m ²	TOTAL-10 MIN g/m ²
13580	2-2-2	2.5 E	0.56 (3.5)	2.3	17.7 (0.75)	24.4		
13680	2-3-2	2.5 E	0.57 (3.5)	2.3	31.6 (0.75)	29.2		
10380	2-1-2	3.5 C	0.88 (2.25)	2.1	6.3 (0.5)	4.5	NO	NO
10480	2-1-3	3.5 C	0.88 (2.25)	2.3	6.2 (0.5)	4.2	HCl	HCl
10780	2-1-6	5.0 D	0.17 (1.75)	0.7	1.3 (1.0)	1.1	PRESENT	PRESENT
10880	2-1-7	5.0 B	0.13 (2.00)	0.7	1.2 (0.5)	1.3		
13780	2-3-2	5.0 E	0.45 (0.5)	0.9	22.8 (0.25)	17.3		
11680	3-2-2	2.5 B	0.69 (0.5)	2.4	NO	NO	26.3 (0.5) 84.4 (5.5)	344
11780	3-2-3	2.5 B	0.76 (0.5)	2.3	NO	NO	85.2 (5.5)	326
11180	3-1-3	3.5 B	1.42 (7.0)	1.5	HF	HF	78.1 (0.5) 54.7 (4.5)	97
11280	3-1-3	3.5 B	1.12 (1.0)	3.1	PRESENT	PRESENT	41.8 (0.5) 109 (3.5)	344
11380	3-1-3	3.5 C	0.58 (1.0)	3.7			38 (0.5) 133 (4.0)	425
12080	3-3-2	5.0 E	0.45 (0.5)	1.7			116 (1.75)	299
12180	3-3-3	5.0 F	0.83 (0.25)	1.9			95 (1.5)	285
12380	4-2-2	2.5 E	0.58 (3.5)	3.3	22.7 (0.75)	52.3	92 (0.75)	137
12480	4-2-3	2.5 F	0.44 (2.75)	3.0	22 (1.0)	50.1	35 (1.0)	101
12680	4-1-2	3.5 E	0.53 (0.5)	1.8	20.1 (0.75)	59.0	(SAMPLE LOST)	
12780	4-1-3	3.5 F	0.57 (0.25)	1.6	37.2 (0.5)	57.5	(SAMPLE LOST)	
12980	4-3-2	5.0 E	0.37 (0.5)	1.0	24.6 (0.25)	41.7	130 (0.25)	167
13080	4-3-3	5.0 F	0.52 (0.25)	1.7	27.2 (0.50)	61.8	85 (0.5)	205
13380	4-1-2	3.5 E	0.58 (3.5)	1.8	24.5 (0.75)	41.0	60 (0.75)	153
13480	4-1-3	3.5 F	NONE	NONE	40.2 (0.5)	70.0	110 (0.5)	215

B through F = SYRINGE TIME INTERVAL SEQUENCES USED IN TAKING SAMPLES

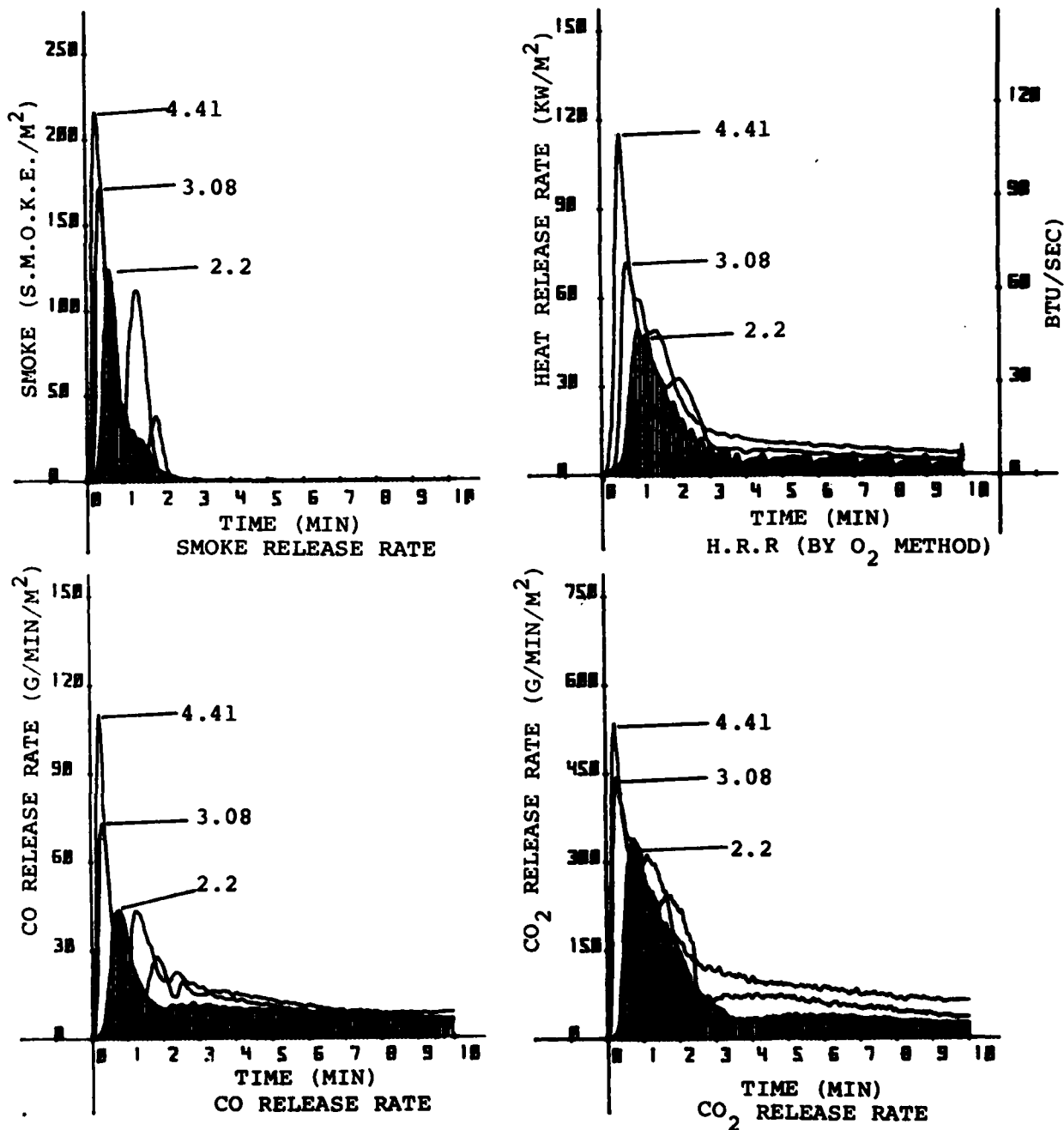


FIGURE 32. CHAS HAZARDS RELEASE RATES COMPARISON OF CEILING PANEL NO. 2 TESTED AT 3 HEAT FLUXES-- 2.2, 3.08 AND 4.41 BTU/FT² SEC (2.5, 3.5 & 5 W/CM²) (Sheet 1 of 3)

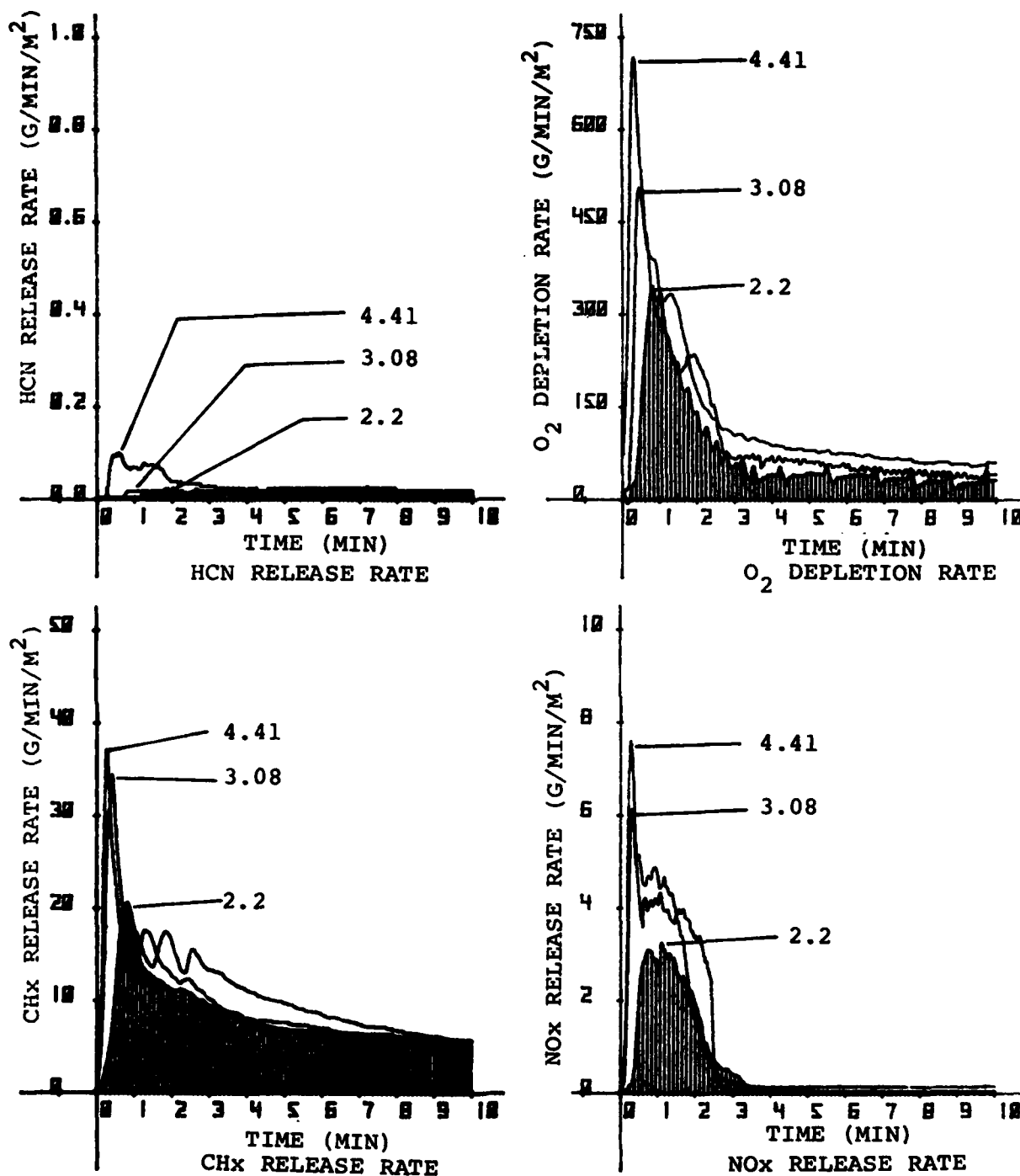


FIGURE 32. CHAS HAZARDS RELEASE RATES COMPARISON OF CEILING PANEL NO. 2 TESTED AT 3 HEAT FLUXES-- 2.2, 3.08 AND 4.41 BTU/FT² SEC (2.5, 3.5 & 5 W/cm²) (Sheet 2 of 3)

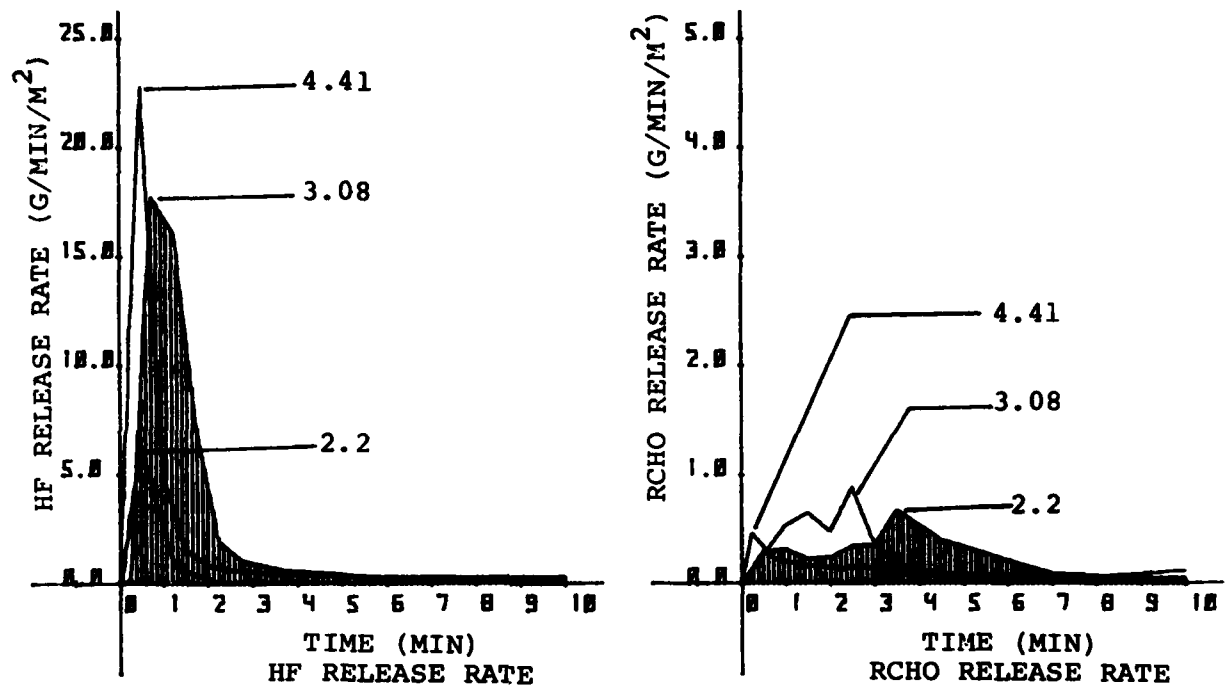


FIGURE 32. CHAS HAZARDS RELEASE RATES COMPARISON OF CEILING PANEL NO. 2 TESTED AT 3 HEAT FLUXES-- 2.2, 3.08 AND 4.41 BTU/FT² SEC (2.5, 3.5 & 5 W/cm²) (Sheet 3 of 3)

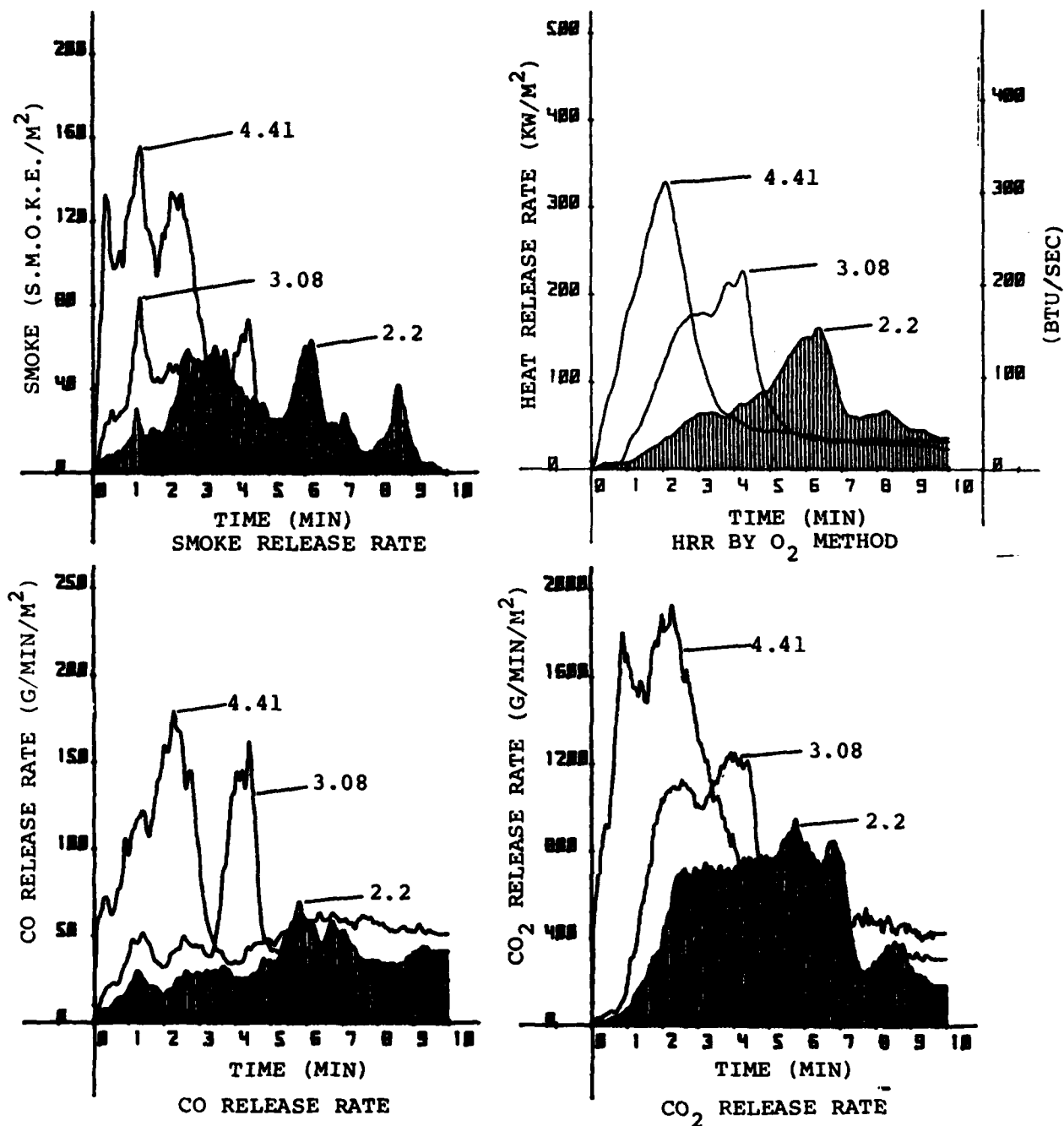


FIGURE 33. CHAS HAZARDS RELEASE RATES COMPARISON OF POPLAR WOOD FACED PANEL NO. 3 TESTED AT 3 HEAT FLUXES-- 2.2, 3.08, & 4.41 BTU/FT² SEC (2.5, 3.5, 5 W/CM² (Sheet 1 of 3)

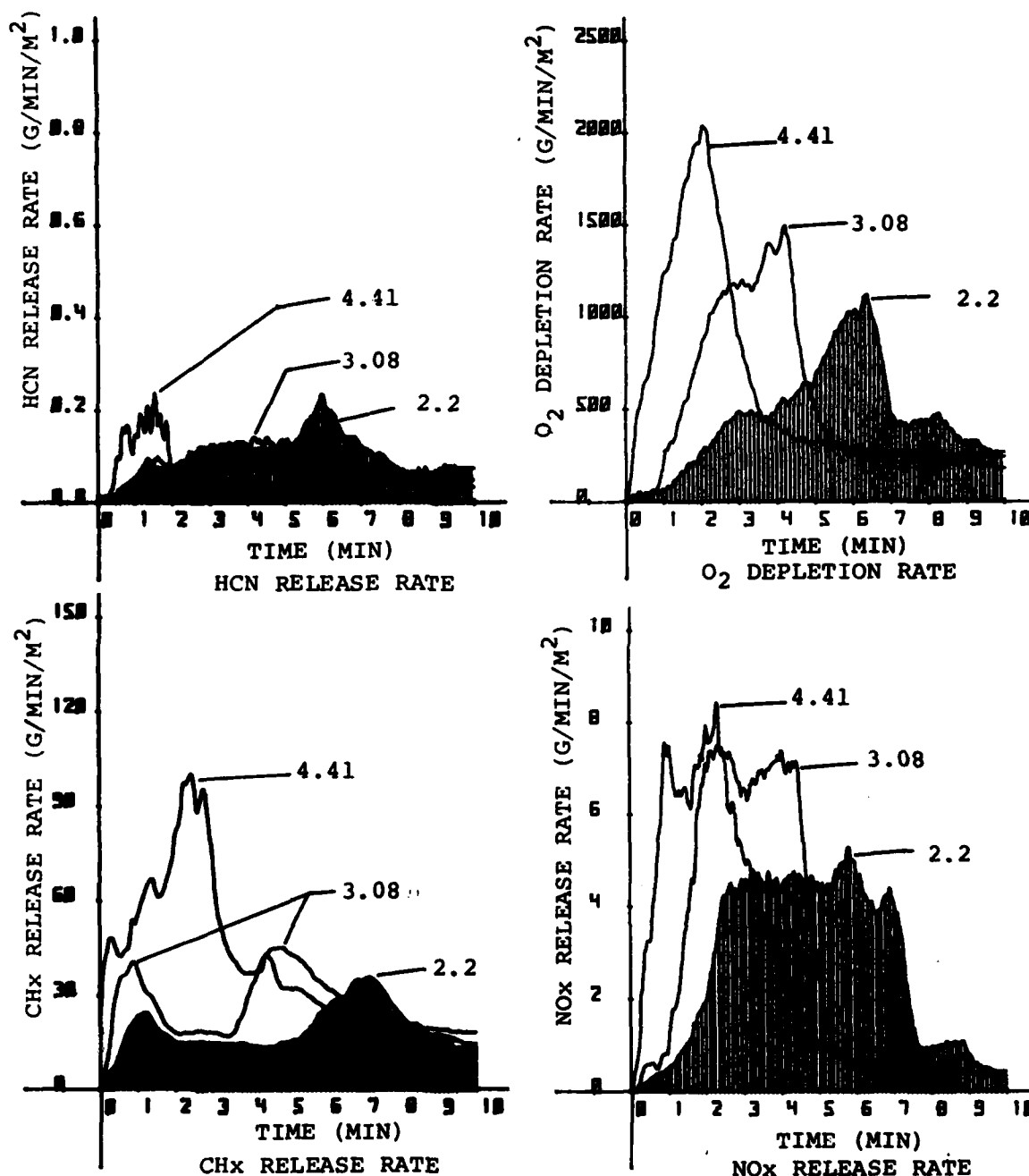


FIGURE 33. CHAS HAZARDDS RELEASE RATES COMPARISON OF POLAR WOOD FACED PANEL NO. 3 TESTED AT 3 HEAT FLUXES-- 2.2, 3.08, & 4.41 BTU/FT² SEC (2.5, 3.5, 5 W/CM² (Sheet 2 of 3)

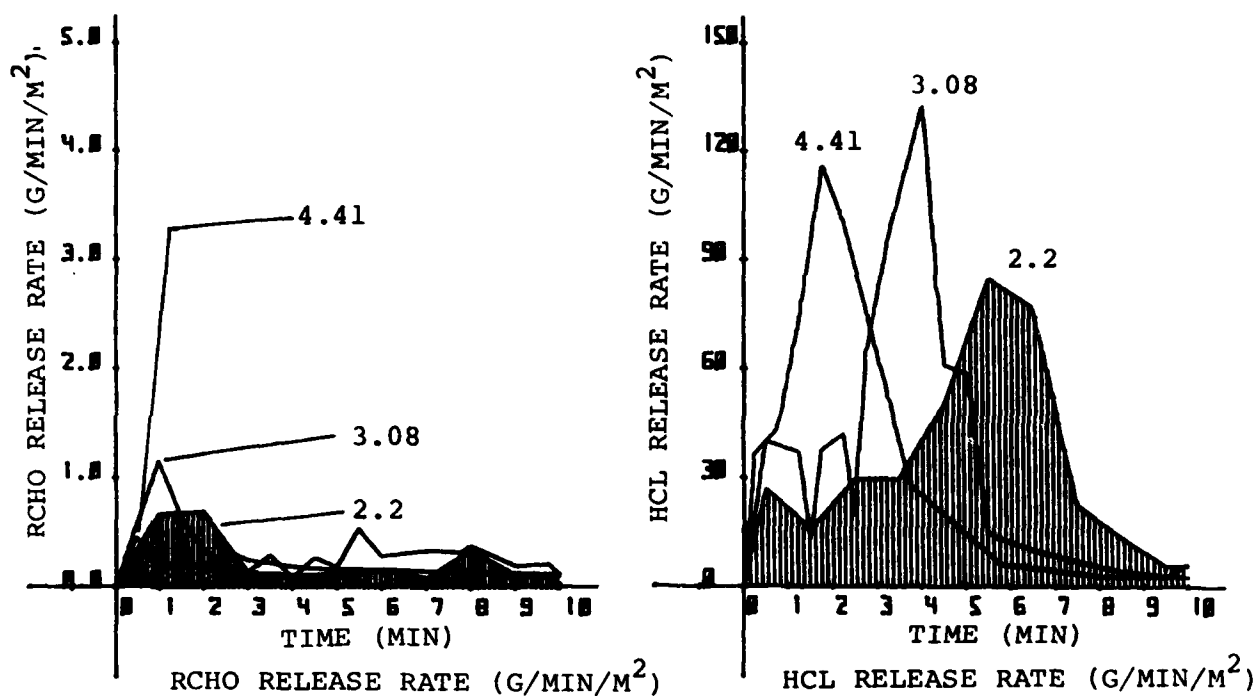


FIGURE 33. CHAS HAZARDS RELEASE RATES COMPARISON OF POPLAR WOOD FACED PANEL NO. 3 TESTED AT 3 HEAT FLUXES-- 2.2, 3.08, & 4.41 BTU/FT² SEC (2.5, 3.5, 5 W/CM²) (Sheet 3 of 3)

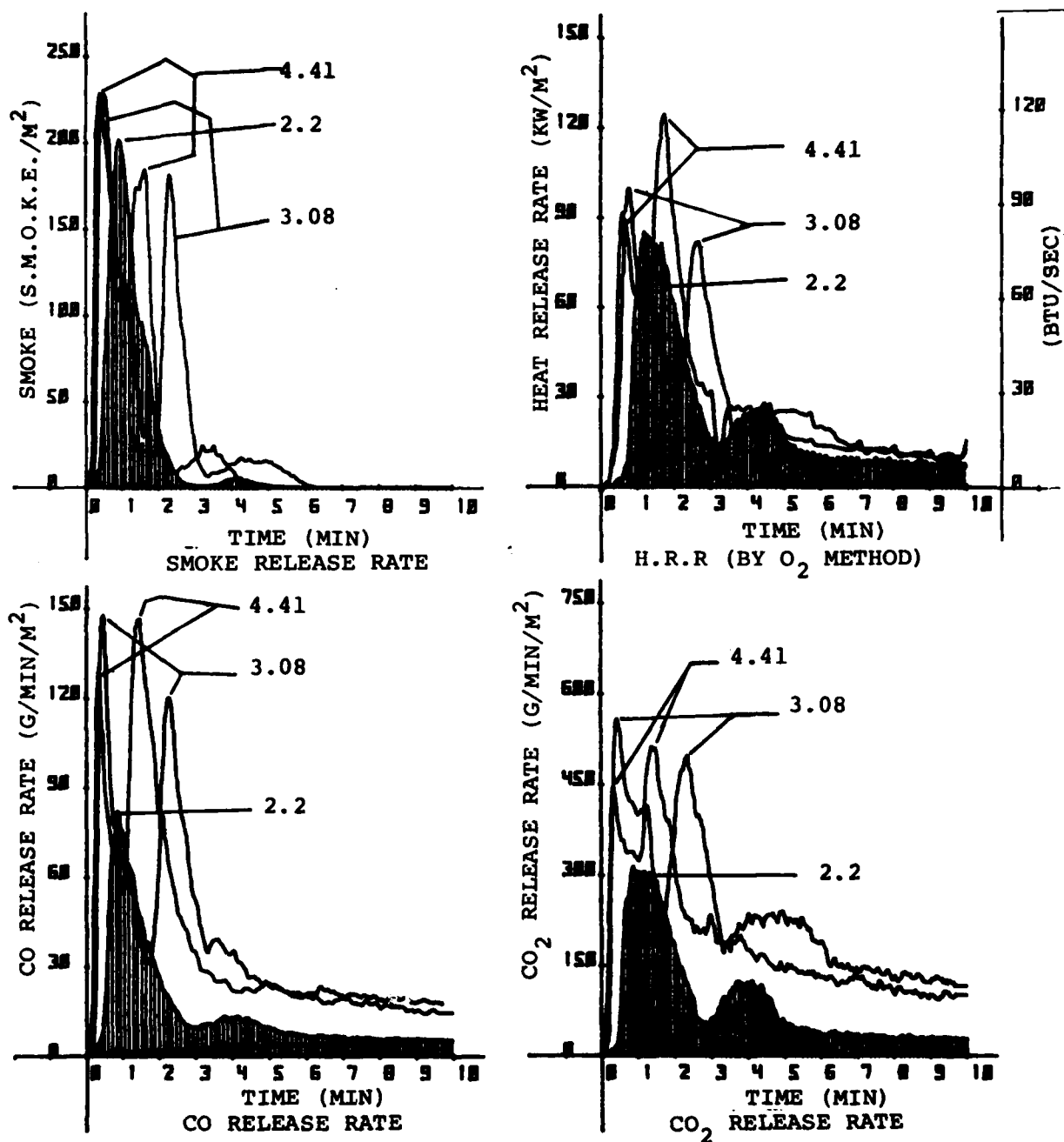


FIGURE 34. CHAS HAZARDS RELEASE RATES COMPARISON OF PARTITION
 PANEL NO. 4 TESTED AT 3 HEAT FLUXES 2.2, 3.08, AND 4.41
 Btu/ft² SEC (Sheet 1 of 3)

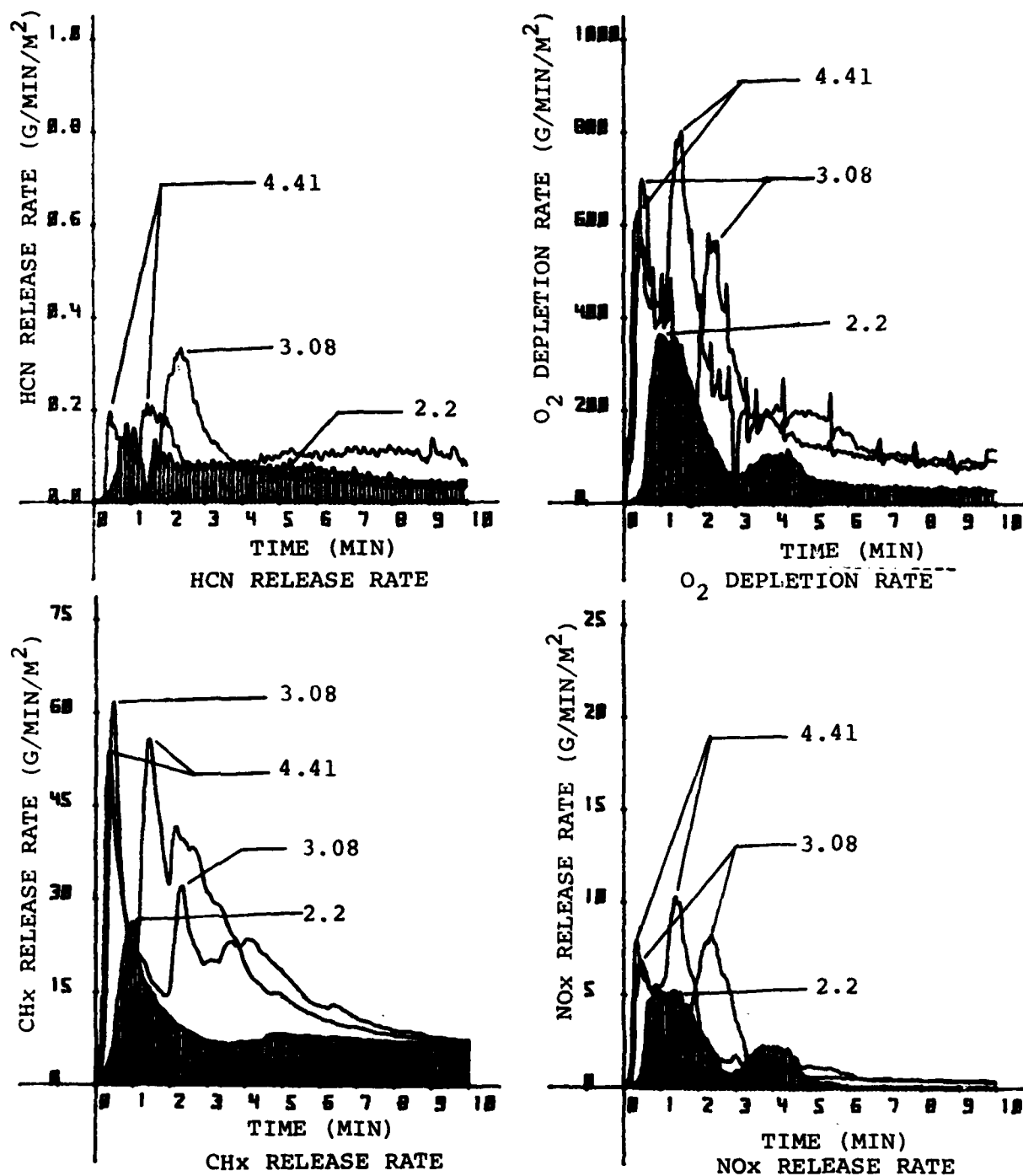


FIGURE 34. CHAS HAZARDS RELEASE RATES COMPARISON OF PARTITION PANEL NO. 4 TESTED AT 3 HEAT FLUXES 2.2, 3.08 AND 4.41 BTU/FT² SEC (Sheet 2 of 3)

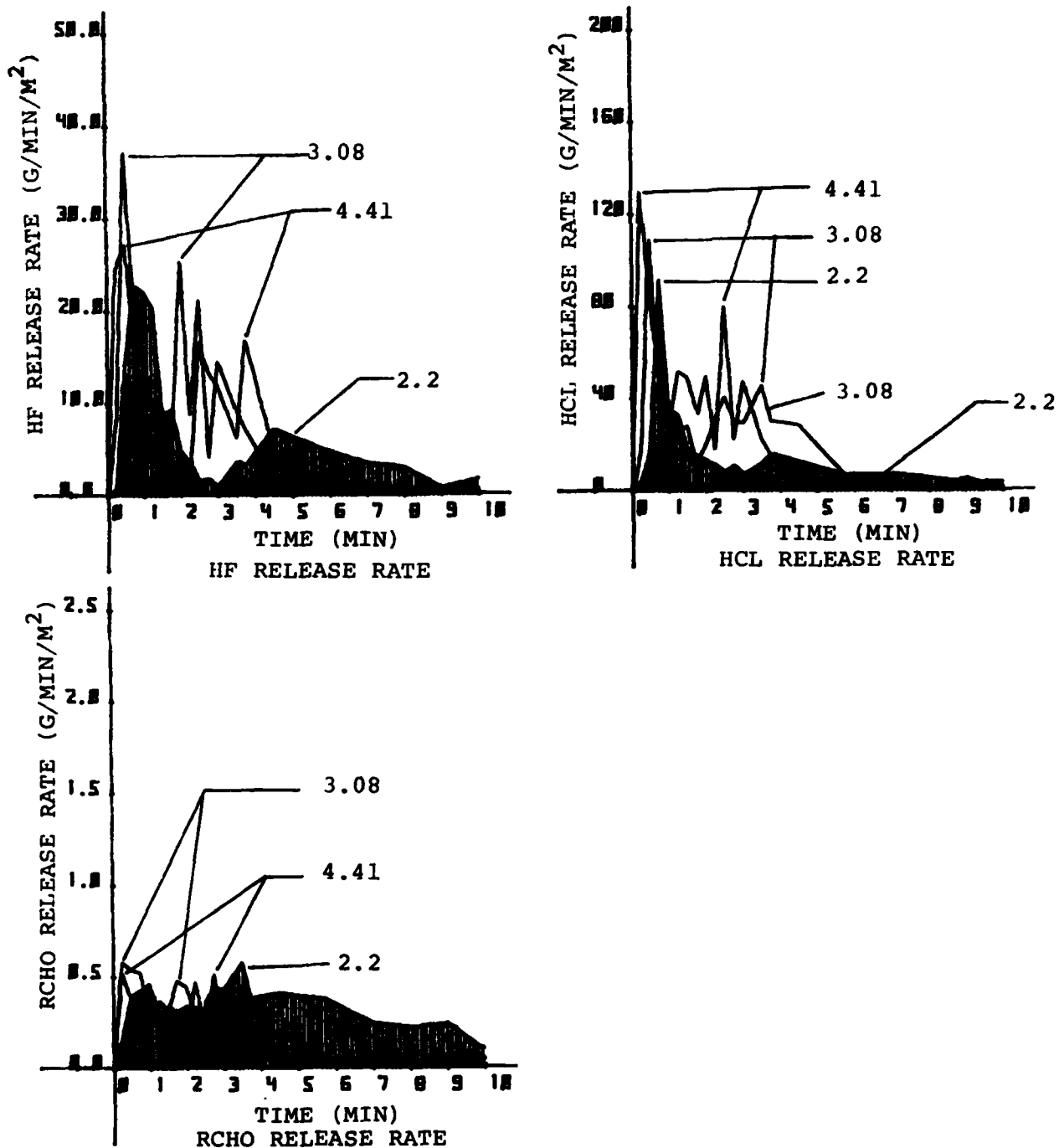


FIGURE 34. CHAS HAZARDS RELEASE RATES COMPARISON OF PARTITION PANEL NO. 4 TESTED AT 3 HEAT FLUXES 2.2, 3.08 AND 4.41 BTU/FT² SE (Sheet 3 of 3)

Figure 35 demonstrates the direct relationship between heat flux and heat release rate for panels 2, 3 and 4. The peak heat release rate data used for these plots were taken from the CHAS curves plotted for each panel specimen tested at 2.2, 3.08 and 4.41 Btu/ft² sec radiant heat fluxes. The heat release rate data used for the plots in Figure 35 were taken from oxygen consumption, Table 9, which in digitized form, were input into the FACP to calculate the CHI for each material.

The peak and 10 minute total heat release values listed for the panel tests summarized in Table 5 were measured by the DTP method. Because of thermal lag effects inherent in the HRR chamber, the DTP heat release measurements reflected in Table 5 were lower than those calculated from O₂ consumption calorimetry. Table 9 shows the oxygen consumption heat release data used in the FACP CHI calculations. This supplements the data in Table 5.

The CHAS/SATS heat release measurements listed in Table 9 indicated that five times more heat was released from the wood faced panel than from the ceiling panel 2 and 2.8 times more heat than from panel 4 in 5 minutes. The air temperatures developed in the CFS tests of panels 2, 3 and 4 were expected to correlate with the CHAS/SATS heat release values.

It was apparent on evaluating the test data that two factors were of primary importance in affecting the CHI calculations. The two factors which will have to be considered in formulating the test procedure and protocols are:

- (1) the uniformity of composition of the material and the degree of randomized burning observed under the established test conditions, and
- (2) the selected test conditions, in particular the heat flux test levels.

Randomized burning of test samples could result in variable CHI values. However, this can be accommodated in the methodology by selecting suitable ranges of response for classifying the hazards generation potential for a material. On the basis of the few materials tested, time compression of the burning events (and hazards release rates) caused by using excessively high test heat fluxes in a test protocol may narrow the CHI values to an unacceptable degree.

Comparison of the changes in CHI value with heat flux may be of value in ranking a material.

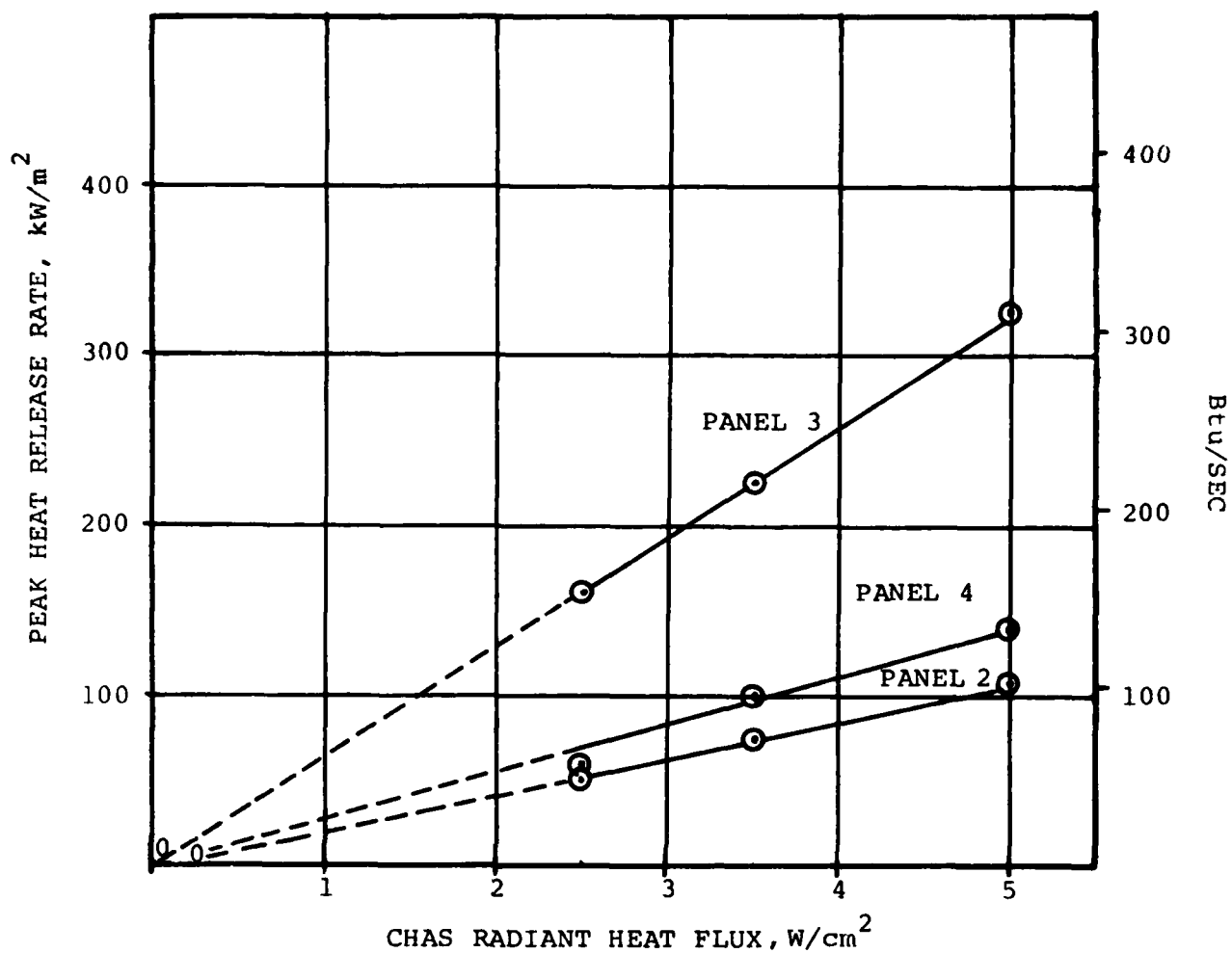


FIGURE 35. PEAK HEAT RELEASE RATE OF PANELS 2, 3 & 4 VERSUS CHAS RADIANT HEAT FLUX TEST LEVEL

TABLE 9
SUMMARY OF CHAS/SATS HEAT RELEASE DATA MEASURED BY THE
O₂ CONSUMPTION METHOD FOR PANELS 2, 3 & 4

PANEL & RUN NO.	HEAT FLUX BTU/FT ² SEC (KW/CM ²)	HEAT RELEASE/FT ² AND M ²				PREDICTED HEAT RELEASE	
		PEAK RATE AT (MIN)		TOTAL IN 5 MINUTES		24 FT ² CFS TEST PANEL	
		KW/M ² AT (*)	BTU/SEC/FT ² AT (*)	KW MIN/M ²	BTU/FT ²	BTU IN 5 MIN	KW IN 5 MIN
<u>Panel 2</u>							
12580	2.2 (2.5)	50 (1.0)	4.65 (1.0)	75	397	9,516	167
13280	3.08 (3.5)	72 (0.75)	6.69 (0.75)	141	745	17,890	314
11080	4.41 (5.0)	107 (0.5)	9.94 (0.5)	196	1036	24,868	437
<u>Panel 3</u>							
11680	2.2 (2.5)	116 (6.2)	10.78 (6.2)	224	1184	28,399	499
11280	3.08 (3.5)	223 (4.3)	20.72 (4.3)	564	2982	71,563	1257
11880	4.41 (5.0)	328 (2.3)	30.47 (2.3)	704	3722	89,326	1569
<u>Panel 4</u>							
12380	2.2 (2.5)	57 (1.2)	5.30 (1.2)	154	811	19,466	343
12680	3.08 (3.5)	100 (0.75)	9.29 (0.75)	285	1501	36,024	635
13180	4.41 (5.0)	138 (1.7)	12.82 (1.7)	312	1643	39,437	696

* NUMBERS IN () ARE MINUTES AT WHICH PEAKS OCCURRED.

ANIMAL RESPONSE- The single rotating wheel in the SATS plexiglas chamber and the associated electrical contact bar provided two biological endpoints, Ti and Td. Either endpoint could have been used to determine which panel material evolved the most hazardous combustion products. Ti was selected to make the comparisons since Td's were not observed as often and the Ti represented a more conservative endpoint related to the concept of emergency evacuations in post crash fire cabin environments. The principal objective of the animal tests was to correlate the Ti results in the CHAS/SATS and the CFS, for comparison with the relative rankings of the panel materials predicted by the FACP.

In the preliminary development of the SATS in 1979, panel number 1 was tested 9 times at 4.41 Btu/ft² sec radiant flux to develop a suitable test procedure and protocol for use in the program. The difficulties of obtaining a Ti or Td endpoint within the time intervals required to completely consume the test materials were exemplified by the data shown in Table 10.

TABLE 10
CHAS/SATS TI TESTS OF PANEL 1 MATERIAL

RUN NO.	SATS FLOW RATE LITER/MIN	FLOW TERMINATED SEC	RAT WT. GRAMS	Ti SEC	Td SEC	REMARKS
47	1	1800	350	-	-	No Results
48	1	1200	356	-	-	No Results
49	4	300	334	-	-	No Results
54	5	180	210	-	-	No Results
NO CHAS DATA	10	180	230	720	-	Td Elicited with CO ₂
NO CHAS DATA	14	216	239	972	-	Td Elicited with N ₂
72	14	192	234	990	1260	V1 Turned Off at Maximum CO *
73	14	204	194	252	720	Same as Above
NO CHAS DATA	14	180	259	750	1200	Same as Above

* See Figure 8.

From the above tests, it became apparent that a flow rate of 14 liters/minute pumped from the HRR calorimeter chamber through the SATS was required to obtain a useable endpoint for comparison purposes.

To evaluate the SATS data, the animal Ti endpoints were calculated inversely (1/Ti) to permit a least squares linear regression analysis of 1/Ti data against the gas release data measured by CHAS.

The data employed for regression analysis and hazards ranking is contained in Table 11. Data from tests on panels 2, 3, and 4 were used since it represented improved methodology. Panel 1 data were not strictly comparable with data from panels 2, 3, and 4 since CHAS instrumentation, sample train changes, and operating modes were improved after panel 1 tests were completed. Table 11 shows the time of termination (1st column) of combustion products flow through the SATS in each test. Flow was stopped in each case when the CO monitor exhibited a peak reading by turning off the ventilating pump and closing valve V1 (see Figure 8). The next three columns show the T_i , T_d and $1/T_i$ (min^{-1}) data observed. The next columns list the quantities (grams) of gaseous products pumped through the SATS while valve V1 was open. Panel 2 lists no results for HCl; and panel 3 lists none for HF since polyvinylchloride was not used in fabricating panel 2 and polyvinylfluoride was not used in panel 3. The last two columns show the total weights of the gases measured (as fed to the SATS) and the milligrams of gases per gram of panel material available to the SATS over the pumping interval (2nd column). The actual effective doses developed in the SATS were not measured. The concentrations of individual gases in the SATS, while not precisely known, were considered to be proportional to the quantities of gas calculated by mathematical integration of the area under the CHAS release rate curves over the time V1 was open. It should be noted that the repeatability of the T_i and T_d values listed in Table 11 apparently do not fall in the same range as the other CHAS measurements. Evaluation of the repeatability can not be made directly since the dose-times for each run were different (valve V1 was not closed at the same time). To evaluate T_i and T_d repeatability, therefore, the integrated dose levels were calculated from the release rate profiles for the time valve V1 remained open to normalize the T_i and T_d data.

Based on the nominal T_i results obtained for the CHAS/SATS tests of all panel materials the apparent ranking for the panels is shown in Table 12. In this table the T_i rankings for the panels at each heat flux test level are shown in descending order from least to most toxic.

Scatter diagrams were plotted to determine the possible correlation of CO yield with the observed T_i for panels 2, 3 and 4, using the data from Table 11. Data points from trouble-free runs were included and data varying by 1.5 (and greater) standard deviations from the mean values were excluded. Figures 36, 37, and 38 show the least squares linear regression plots relating $1/T_i$ to the "feed" quantity (grams) of CO flowing through the SATS chamber.

TABLE 11
CALCULATED ANIMAL TIMES TO INCAPACITATION AND GAS YIELDS FLOWING THROUGH SATS

MATERIAL DESCRIPTION & TEST HEAT FLUX	VALVE (V1) OFF (SEC)	BIOLOGICAL ENDPOINT		TOTAL (INTEGRATED) COMBUSTION GAS YIELDS (t = 0 to t = VALVE V1 CLOSED)									TOTAL NG GAS /GRAM SAMPLE
		T _i (SEC)	T _d (SEC)	CALC'D L/T _i (MIN ⁻¹)	GRAMS OF GASES AT NORMAL TEMP. & PRESS								
					CO	CO ₂	HCN	NO/NO _x	RCHO	HCl	HF		
PANEL 2	79	1170	1700	0.051	1.384	13.4	<0.001	0.144	0.012	-	0.474	15.43	99
2.2	72	1460	-	0.041	1.227	10.6	<0.001	0.118	0.017	-	0.342	12.26	79
	72	675	1180	0.089	1.9	15.4	<0.001	0.200	0.021	-	1.208	18.74	121
	72	415	835	0.145	1.95	16.77	<0.001	0.252	-	-	-	18.97	121
3.08	52	700	1300	0.086	1.545	14.28	<0.001	0.152	0.013	-	0.216	16.21	104
	60	1075	1575	0.056	2.333	17.78	<0.001	0.207	0.030	-	0.239	20.50	131
	55	490	1250	0.122	2.614	19.90	<0.001	0.243	0.009	-	0.053	22.82	146
4.41	51	365	865	0.164	2.967	22.08	<0.001	0.251	0.005	-	0.142	25.45	165
	51	585	750	0.103	2.898	20.84	<0.001	0.216	0.008	-	0.031	23.99	155
	58	430	850	0.140	2.994	21.31	<0.004	0.281	0.017	-	0.795	25.39	160
PANEL 3	655	985	1210	0.061	7.473	112.31	0.023	0.617	0.056	7.98	-	120.5	842
2.2	N.C.	1800	-	0.033	7.263	98.71	0.018	0.581	0.054	7.57	-	114.2	794
	174 250/272	1355	1650	0.044	3.376	33.76	<0.004	0.196	NOT RUN	3.83	-	40.25	266
	160- 540	365	695	0.164	21.35	163.44	0.020	2.363	0.010	3.52	-	190.7	491
3.08	274	335	735	0.179	7.23	86.88	0.014	0.526	0.042	7.27	-	102.0	682
	N.C.	700	-	0.086	13.04	196.97	0.015	0.578	0.040	6.95	-	217.6	1487
4.41	186	270	535	0.222	7.99	70.78	0.019	0.443	0.021	4.99	-	84.2	571
PANEL 4	107	540	1300	0.111	4.57	22.46	0.006	0.414	0.037	3.37	1.527	32.4	119
2.2	94	445	1060	0.135	3.93	18.85	0.001	0.297	0.029	2.05	1.343	26.5	97
	116	220	500	0.273	7.53	42.04	0.003	0.529	0.051	LOST	1.519	-	
3.08	203	138	258	0.435	15.39	82.89	0.023	1.111	0.079	LOST	2.788	-	
	175	80	300	0.750	13.81	56.90	0.018	0.865	0.042	8.62	1.784	82.0	306
4.41	185	100	310	0.600	15.22	62.58	0.023	0.920	0.060	10.11	2.59	91.5	342

NC = VALVE NOT CLOSED DURING RUN - = GAS NOT PRESENT; TOTAL GAS (g) NOT DETERMINED

* See Figure 8

TABLE 12

ANIMAL TI HAZARDS RANKINGS FOR TEST PANELS (CHAS/SATS)

PANEL NO.	HEAT FLUX BTU/FT ² SEC	AVERAGE TI SEC	RANKING*		
			AT EACH HEAT FLUX		
			2.2	3.08	4.41
1	2.2	870	-	-	1
	3.08				
	4.41				
2	2.2	1102	2	2	2
	3.08	888			
	4.41	468			
3*	2.2	(355) 985	(4) 3	(4) 3	3
	3.08	(126) 350			
	4.41	(97) 270			
4	2.2	493	(3) 4	(3) 4	4
	3.08	179			
	4.41	90			

- = Insufficient data to calculate parameter.

1, 2, 3, 4 = Assigned ranking; 1 to 4 least to most toxic

* = Ti values and rankings in parenthesis were normalized for comparison with the other panels. Panel No. 3 samples were 6 x 6 inches whereas the other samples were 10 x 10 inches in size. The normalization factor used was 0.36 (36 in²/100 in²).

C1=-4.652944E-03
C2= 4.778410E-02

$$Y = C1 + C2 * X; Y = 1/T1$$

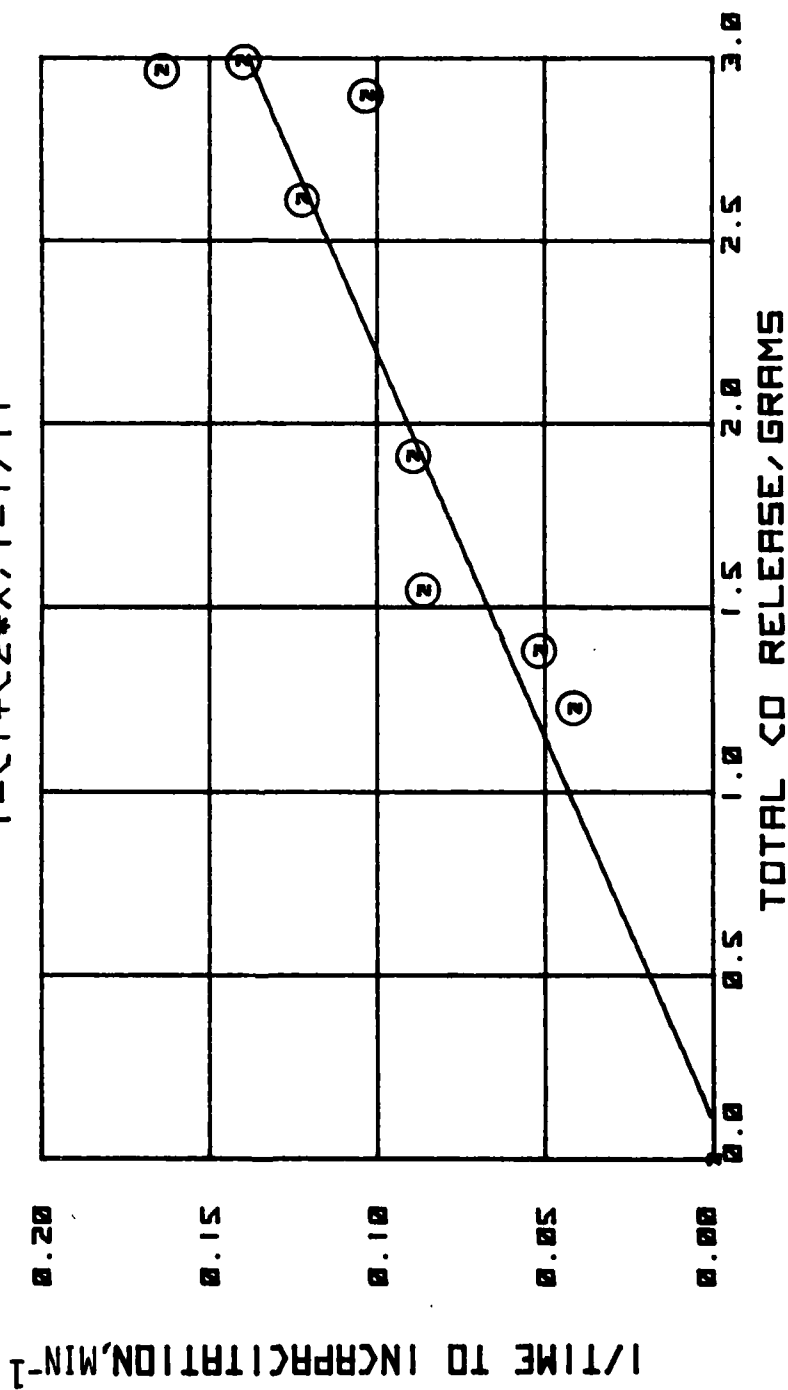


FIGURE 36. CORRELATION OF $1/T1$ (MIN^{-1}) VALUES WITH PANEL 2 CHAS/SATS CO YIELDS

C1=-4.401277E-03
C2= 7.020801E-03

$$Y=C1+C2*X; Y=1/TI$$

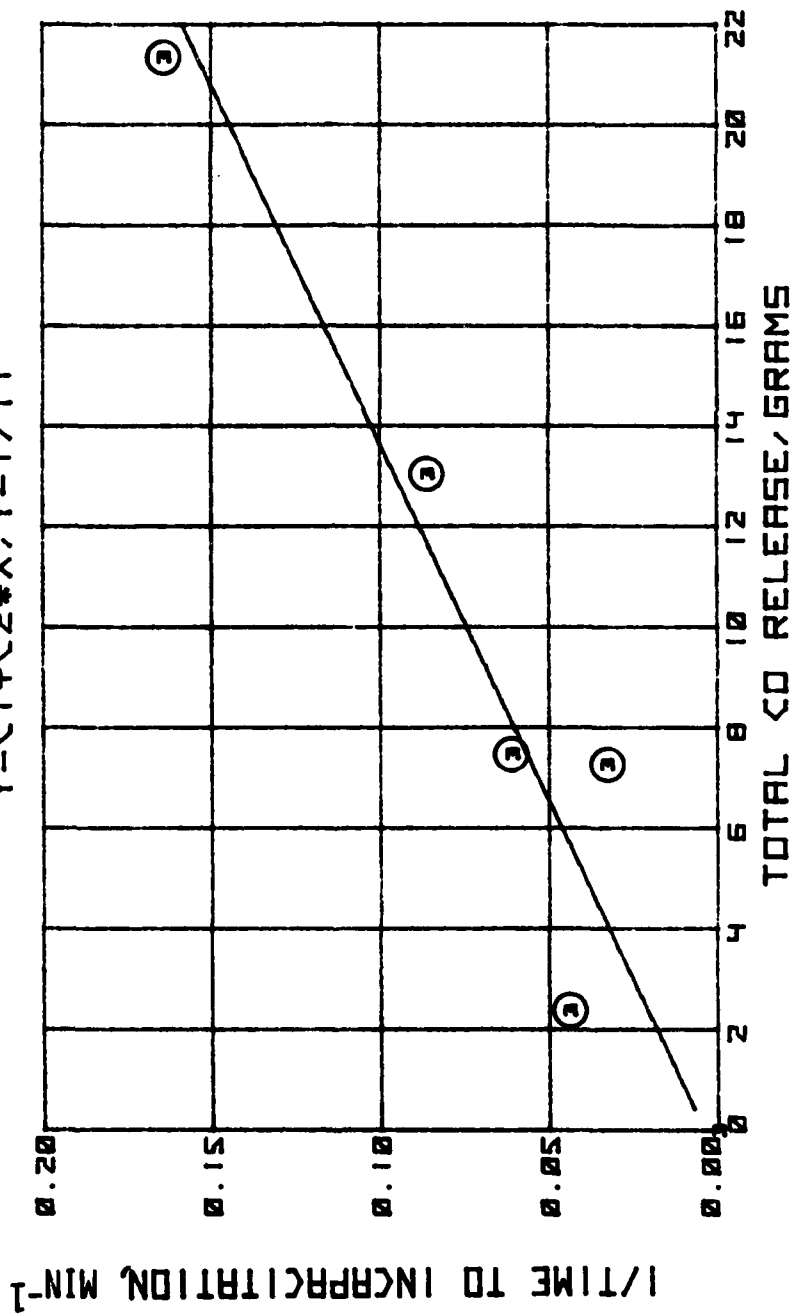


FIGURE 37. CORRELATION OF 1/TI (MIN⁻¹) VALUES WITH PANEL 3 CHAS/SATS CO YIELDS

C1=-8.217515E-03
C2= 3.436881E-02

$$Y = C1 + C2 * X; Y = 1/T1$$

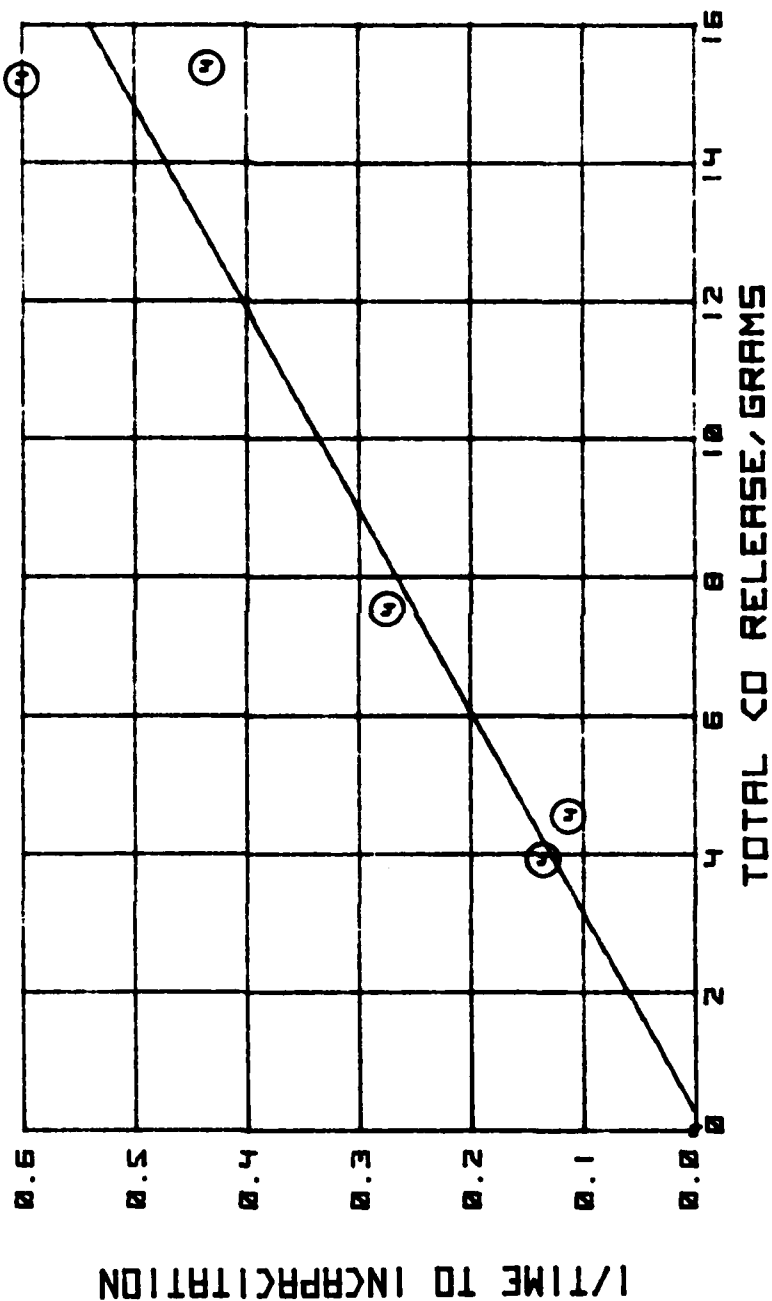


FIGURE 38. CORRELATION OF $1/T_1$ (MIN^{-1}) VALUES WITH PANEL 4 CHAS/SATS CO YIELDS

The $1/T_i$ values for these panels appear to correlate with CO yield to a significant degree. Thus, the regression lines show positive slopes, i.e., high yields of CO at increasing heat flux levels correlate with decreasing T_i 's under the experimental conditions for the tests. In this analysis the regression line was assumed to fit a simple linear relation of the form:

$$1/T_i = C_2 (g \text{ CO}) + C_1$$

Where: C_2 = Slope
 C_1 = Intercept

Considering the variability in the burning profiles evidenced by the CHAS release rate parameters and the small number of available data points, the correlation of T_i with CO yield was better than expected. The coefficient of determination (R^2) for panel 2 was 0.95 showing a good fit to the data in Figure 36. The regression line for panel 2 intercepts the $1/T_i$ axis at -.0047 which, on the basis of the variability in animal response and other test parameters appeared to be insignificantly different from zero. The intercepts for panels 3 and 4 also show small deviations from zero in Figures 37 and 38. The regression constants for panels 2, 3 and 4 are summarized in Table 13.

TABLE 13

CORRELATION OF CO YIELDS WITH $1/T_i$ VALUES (PANELS 2, 3 AND 4)

PANEL NO.	R	R^2	C_2^*	C_1^*
2	0.976	0.95	0.0478	-.0047
3	0.969	0.94	0.0070	-.0044
4	0.974	0.95	0.034	-0.0082

R = Correlation Coefficient
 R^2 = Coefficient of Determination
 $*$ = $1/T_i \text{ (min}^{-1}\text{)} = C_2 (g \text{ CO}) + C_1$

The good correlation of T_i with CO yields might be expected since the test protocol provided for exposure of the rats to the peak CO emission environment (valve closed at peak CO emission time). However, the correlation indicates the test protocol provides a reasonably acceptable method for ranking the materials using animals. As shown by the release rate profiles, the other gases track fairly closely with the CO emissions.

Additional scatter diagrams relating $1/T_i$ with grams of gas available to the SATS were plotted for RCHO, HF, HCl and NO_2 . Widely scattered data points generally were observed for these reactive irritant gases, and the regression analysis coefficients of determination (R^2) were much lowered than for CO. Insufficient data points were available to obtain a statistically significant fit of the data. A scatter plot of $1/T_i$ versus the mg/g of HCl gas evolved by panel 3 appeared to exhibit a negative slope, indicating that an increase in HCl concentrations delayed the time to incapacitation. This result was consistent with similar behavior noted in other work for polymers emitting relatively high concentrations of HCl. Rats have been observed to breathe shallowly during short term tests when exposed to irritants. The degree of penetration into the lungs is reduced by this mechanism and unless the animal is forced to breathe high concentrations, T_i is delayed because of lower absorption rates of systemic toxicants such as CO and HCN. A T_i endpoint will finally be reached due to the reduced minute respiratory volume and the onset of anoxia. Both the front and back surfaces of panel 3 were constructed with PVC (polyvinylchloride) decorative layers adhesively bonded to poplar wood facings. PVC can yield up to 56% HCl by weight when completely decomposed in a high temperature environment.

The correlation of the T_i values with the combined concentrations of active gases introduced into the SATS during the time valve V1 remained open was investigated. In this effort, the measured weights of the more toxic gases, CO, HCN, NO/NOx, RCHO, HCl, and HF were summed and normalized to the test panel weights as milligrams of gases per gram (mg/g) of panel material used for each test. These values were calculated using the gas evolution data in Table 11 and the corresponding sample weights. A regression analysis plot of the $1/T_i$ experimental values against the mg/g concentrations available from each panel material at the 3 heat flux levels showed a linear relationship for all panels. Table 14 contains the linear equation constants and the correlation coefficients for panels 2, 3 and 4.

TABLE 14

CORRELATION OF COMBINED TOXIC GAS YIELDS WITH $1/T_i$ VALUES (EXCLUDING CO_2)

PANEL NO	R	R^2	C2 *	C1 *
2	0.80	0.64	0.0066	-0.0233
3	0.89	0.79	0.0024	-0.0513
4	0.94	0.88	0.0076	-0.1077

R = Correlation Coefficient

R^2 = Coefficient of Determination

* = $1/T_i \text{ (min}^{-1}\text{)} = \text{C2 (mg gases/g sample)} + \text{C1}$

The slope values (C2) of the linear regression equations indicated non-parallel response of the animals to the combined toxic gas species dosages evolved by the panel materials. The $1/T_i$ versus mg/g lines for Panels 2 and 4 were nearly parallel, which may have been the result of similar chemical compositions and

gaseous breakdown products mixtures. However, while these test panels were cut to the same size (10 x 10 in.), the panel 2 test specimens weighed 0.25 lb (112 g) less than the Panel 4 test specimens. The resulting combustion products dosages available to the SATS thus were reduced in tests of panel 2 at all heat flux levels.

None of the CHAS/SATS runs on Panel 2 resulted in Ti's in less than 5 minutes, as reflected by the data in Table 11. Panel 4 evolved up to 7 times more CO and 2 to 3 times more HF than Panel 2. HCl gas was an additional product of the decomposition of panel 4. Panel 3 evolved the greatest total quantity of gas by weight at all heat fluxes. Most of this increase was accounted for by the high CO₂ production (due to burning the wood facing material). A relative ranking based on comparative evolution levels of CO, HCl, and HF and other gases from panels 2, 3 and 4 substantially agreed with the animal rankings shown in Table 12. Only one run with panel 3 material resulted in a Ti occurring in less than 5 minutes. The most obvious reason for the nominal differences in Ti ranking observed for panel materials 3 and 4 was attributed to the difference in area (36 in² for panel 3, 100 in² for panel 4). As previously mentioned, panel 3 test specimens were reduced in area to permit successful measurements of the fire response parameters in the CHAS due to its violent burning. The bias in Ti values tending to show Panel 3 materials were less toxic than panel 4 materials, under the test conditions, would reverse if the respective specimens had been run as 100 in² samples.

The CO concentration - Ti correlations shown in Figures 36, 37 and 38 indicated that CO contributed to the observed biological response. To explore this further, the integrated "apparent" doses (assuming complete mixing and interchanging of the SATS atmosphere) were calculated using the standard gas law in terms of ppm CO. Using the Crane formula (Reference 19) for estimating the Ti for rats exposed to pure CO gas/air concentrations, the expected Ti values were calculated. The calculated Ti values were plotted against the experimentally observed Ti values obtained from runs made on Panels 2, 3, and 4.

Figure 39 shows a linear regression plot of the data. The correlation coefficient of 0.977 indicated CO was certainly an important contributor to the biological endpoints observed in these experiments. The slope value for the regression line (0.4846) should have been close to unity to indicate that CO was the major contributor to the observed Ti's. This question could not be resolved in this case because the actual concentrations of the various combustion products gases (including CO) were not directly measured in the SATS for each experiment. The correlation line in Figure 39 indicates either that the CO concentrations calculated from the CHAS CO evolution curves did not describe the average CO concentrations developed in the SATS, or that other gas species affected the results. Based upon the free volume of SATS (5.4 liter), the pumping rates, and the time the isolation valve, V1, remained open during a test, the apparent 50% dilution inferred from Figure 39 seems to be reasonable.

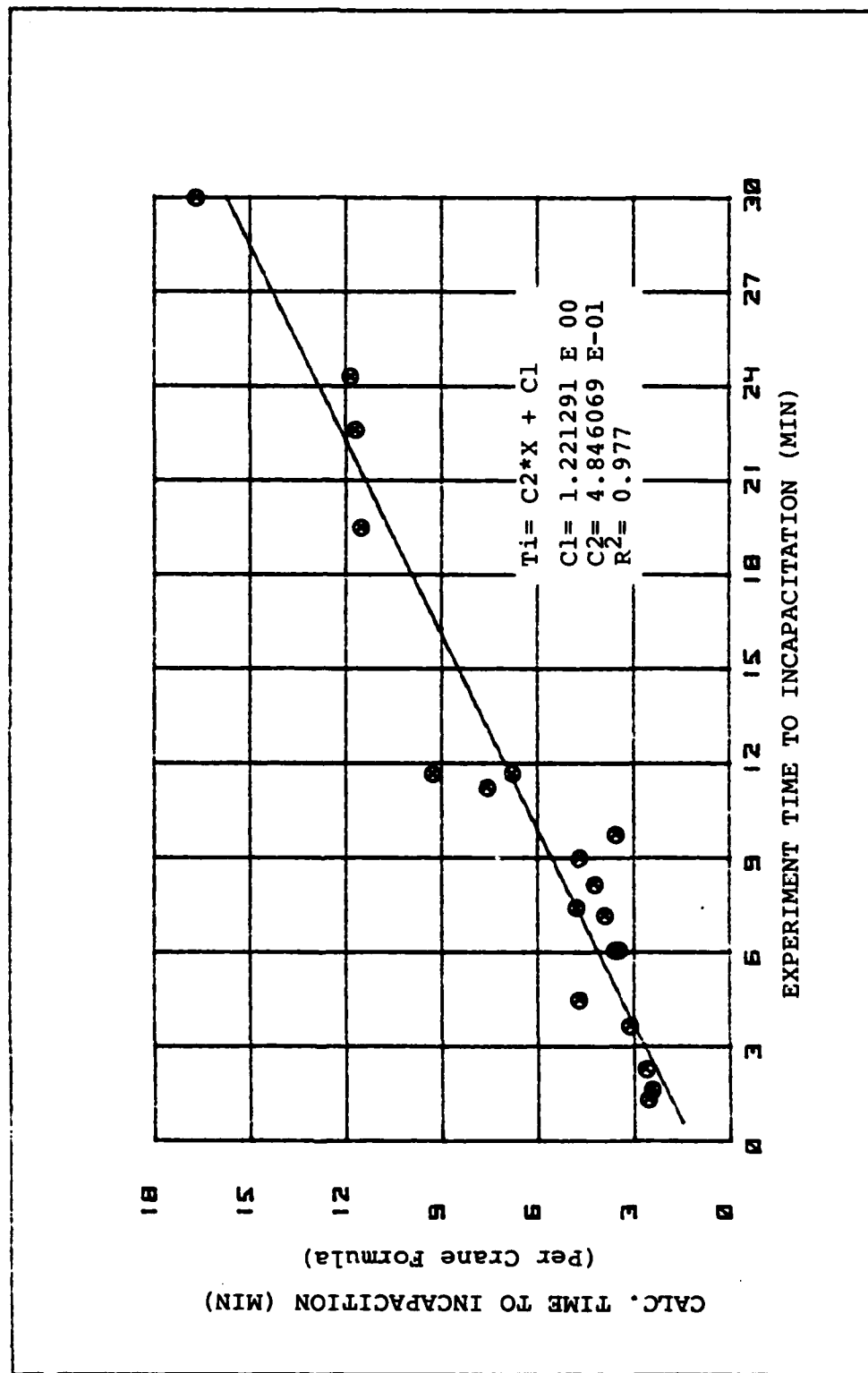


FIGURE 39. GROUPED DATA FOR PANELS 2,3 and 4--COMPARISON OF CALCULATED AND OBSERVED T_i VALUES

COMPARISON OF CFS TEST RESULTS WITH CHAS/SATS AND SINGLE AND TWENTY ZONE COMPUTER PROGRAM OUTPUTS

The CHI Program planned approach provided for large scale testing of 4 X 6 ft. panels in the CFS at radiant flux levels comparable to those used for CHAS/SATS tests of the smaller specimens cut from the ends of the large panels. Each 4 X 6 ft. section of the four panels was burned in the vertical mode employing a multiple propane ignition flamelet. Some improvements in the instrumentation, ignition flamelet configuration and mounting of the test panels were incorporated in the setup and in the operational procedures used in later tests (Panels 2, 3, and 4). These have been previously described in the experimental approach section.

CFS test data collected from runs on Panels 2 and 3 at 2.2, 3.08, and 4.41 Btu/ft² sec radiant flux levels were compared with data output by the 1-zone and 20-zone Fortran FACP's. Comparison of the FACP outputs (based on CHAS/SATS input data) with the temperature, smoke, and gas release profiles plotted from the CFS measurements were employed to modify and improve the prediction capabilities of the single and 20 zone FACP's. After appropriate evaluation, the adjusted independent variables were introduced and the programs were rerun to compare the FACP hazards predictions and CHI values for Panel 4 which was considered as an unknown material, with CFS test results.

PANEL TESTS IN THE CFS

Table 15 identifies the panels tested in the CFS, the average heat flux test levels, weight loss, quantities of exhaust gases evolved, animal toxicities and observed test variables for each experimental burn test.

The weight loss data shown in columns 4 and 5, Table 15, and the CHAS MLT data were directly compared by scaling the CHAS panel weight loss data to the same panel sizes used in the CFS tests. Comparison of the weight loss curves from the laboratory tests of each panel material with those of the corresponding large scale tests gave direct evidence of the degree of conformity of the mass burning rates in the two environments. Heat flux test levels were the only independent test variables that could be held approximately the same in the two test regimes. The ratios of airflow rates through the CFS and CHAS to the test sample areas and weights could not be set to the same values due to operational constraints. However, these variables and others such as the respective chamber volumes and internal surface areas were included in the FACP's to make comparisons of the fire response data output by the CHAS/SATS and the CFS. Variations in mass burning rates of the panel materials in the two environments are shown in Figures 40, 41, and 42. Eight of the weight loss curve comparisons showed that the panel materials burned more completely in the CHAS than in the CFS. The one exception to this was Panel 3, tested at 3.08 Btu/ft² sec, in which the CFS panel appeared to be more completely consumed in 300 seconds. Panel 3 at 4.41 and Panel 4 tested at 4.41 and 3.08 Btu/ft² sec appeared to deviate from CHAS data to the greatest extent. Spall-off of burned and charred residue, occurring within 300 seconds, were included in the data. Therefore actual nominal comparisons were approximations. However, the panel samples for the most part did appear to burn less completely in the CFS. This may have been due to airflow differences, variations in the heat flux level patterns over the sample surfaces, and the greater inhibiting affect of non-flammable gas evolutions (HF, HCl, H₂O) that reduce the flame propagation and surface involvement rates over the larger sample surface areas burned in the CFS.

TABLE 15
CFS BURN TEST GAS EVOLUTIONS AND WEIGHT LOSSES - PANELS 2, 3, AND 4

CFS TEST NO.	PANEL NO.	HEAT FLUX BTU/FT ² SEC	PANEL WT. - LBS INITIAL	① 5 MIN	PRESSURE PEAKS OBSERVED SEC	GAS AND AVERAGE RPM				TEST OBSERVATIONS
						AT CFS EXHAUST IN 10 MIN				
						HCN	HCL	HF	RCHO	
4	2-2	2.2	11.93	9.62	52	0.17 (6.21)	2.25 (61.0)	0.46 (22.65)	0.28 (9.05)	Propane pilot did not rotate until 150 sec. PVC melted off surface - no flames. Resin burned out of facing leaving charred core. Backing charred only on honey-comb interface. Test animals did not survive (50 min, exposure)
5	3-2	2.2	31.00	13.91	1st 95 2nd 120 3rd 149 4th 256	1.78 (64.89)	12.07 (327)	0.64 (31.79)	0.49 (16.22)	Propane pilot rotated late PVC melted/decomposed with flame. Center burned out with 1-3 in remaining at edges. All test animals survived.
6	2-4	2.2	11.68	9.62	77	0.54 (19.75)	5.2 (141)	1.25 (61.64)	0.28 (9.16)	Propane pilot rotated properly. PVC decorative film melted/decomposed w/flame. All test animals survived.
7	2-1	3.08	11.93	9.21	1st 60 2nd 135	0.88 (32.16)	4.68 (127)	0.99 (48.9)	0.26 (8.64)	Propane pilot OK Post test appearance same as test No. 4. All test animals survived.
8	3-1	3.08	31.25	12.00	1st 62 2nd 96 3rd 118 4th 248	2.86 (104.6)	33.14 (897)	1.82 (89.87)	0.46 (15.0)	Flames continued beyond 900 seconds. All test animals survived.
9	2-3	4.41	12.11	8.83	1st 30 2nd 120	0.92 (33.71)	4.47 (121)	0.73 (36.03)	0.2 (6.45)	All test animals survived.
10	3-3	4.41	30.95	11.47	1st 73 2nd 205 3rd 267	2.52 (92.02)	31.46 (851.5)	1.19 (58.72)	0.47 (15.4)	Same as Run No. 8. Only one test animal survived.
11	4-3	4.41	20.65	15.76	1st 37 2nd 118	1.91 (69.74)	12.46 (337.3)	1.69 (83.51)	0.2 (6.72)	Bypass valve accidentally open for 20 seconds PVC/PVC coatings melted/burned front & back Resin burned out of facing, backing & core All test animals survived
12	4-1	3.08	20.62	17.00	1st 54 2nd 124	1.36 (49.65)	5.44 (147.3)	0.71 (34.87)	0.1 (3.43)	PVC/PVC melted/decomposed with flame on both front and back All test animals survived
13	4-2	2.2	21.30	17.86	1st 73 2nd 156	1.02 (37.42)	7.99 (213.7)	1.49 (73.4)	0.16 (5.16)	PVC/PVC melted/decomposed w/flame on front-only partially on back All test animals survived

① Includes weight lost due to spalling

② Calculated using gas law and CFS flow rate of 875 ft³/min.

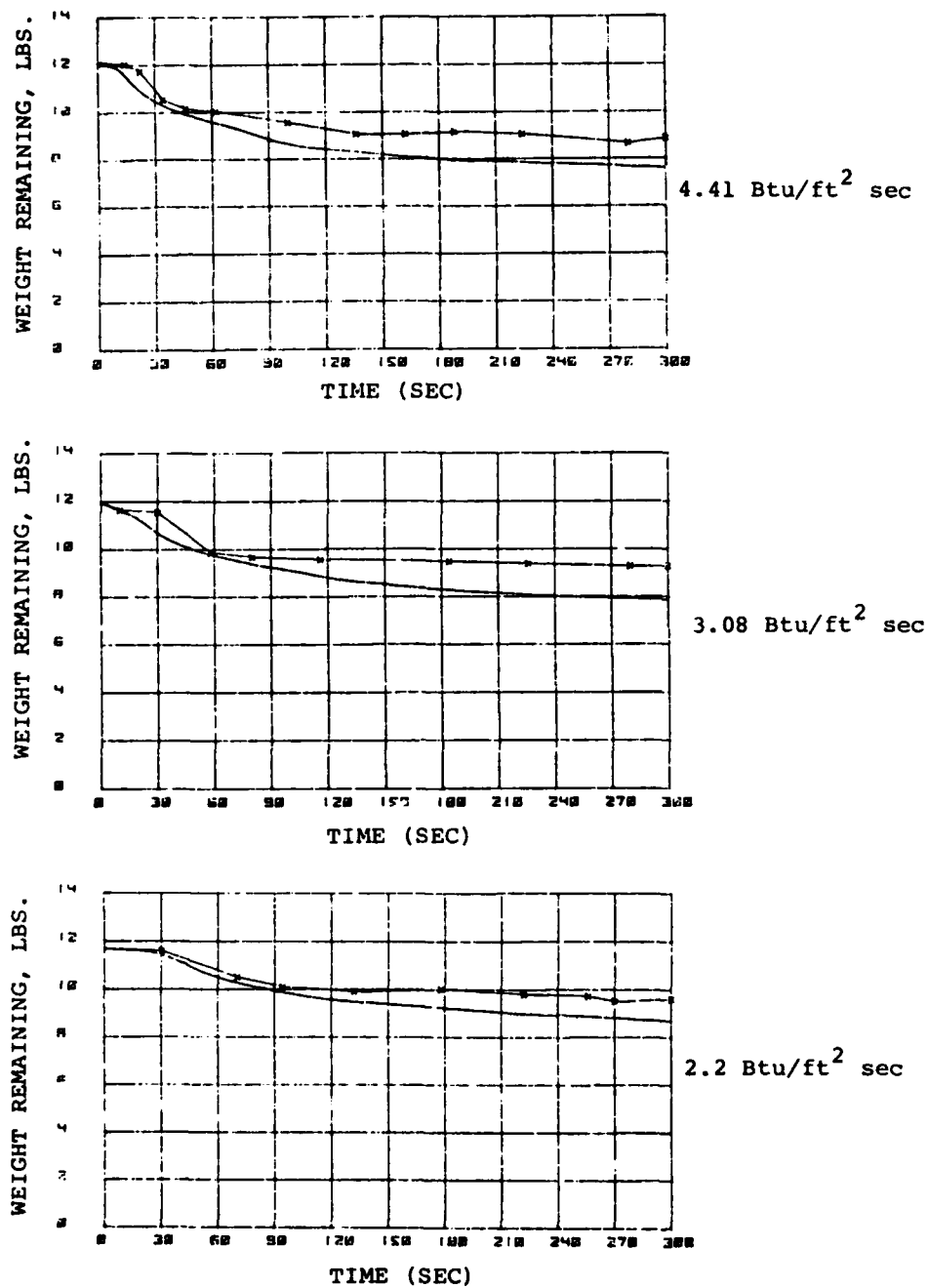


FIGURE 40. COMPARISONS OF CHAS AND CFS WEIGHT LOSS BURN PROFILES OF PANEL 2 MATERIAL (**--CFS TEST; — = CHAS TEST PLOT CALCULATED FOR PANEL SIZE USED IN CFS TESTS)

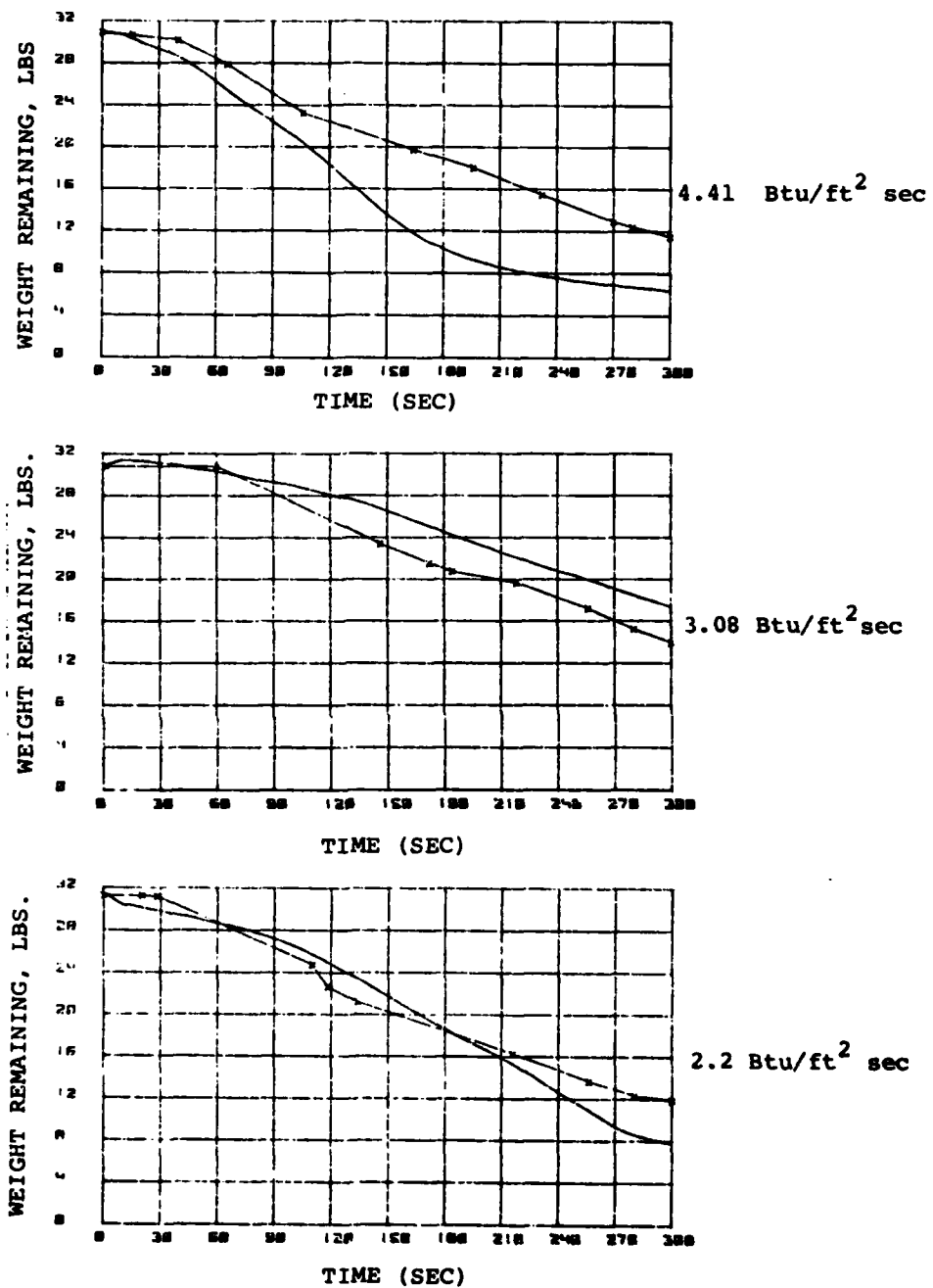


FIGURE 41. COMPARISONS OF CHAS AND CFS WEIGHT LOSS BURN PROFILES OF PANEL 3 MATERIAL (*--* = CFS TEST; — = CHAS TEST PLOT CALCULATED FOR PANEL SIZE USED IN CFS TESTS)

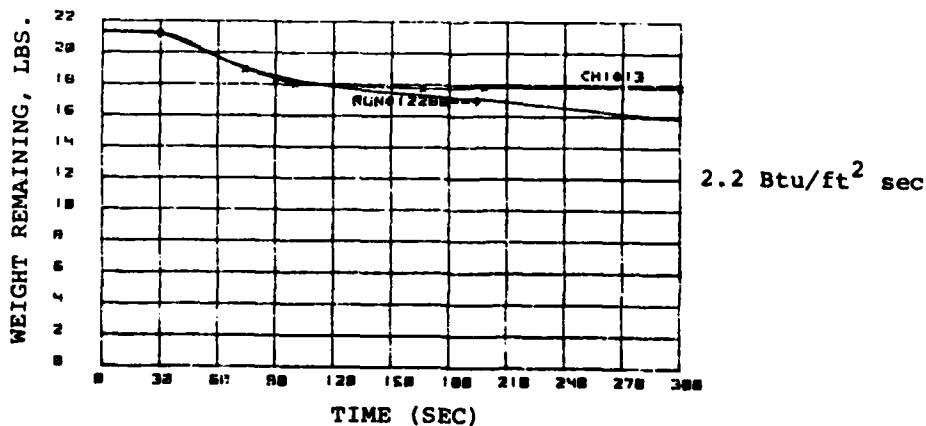
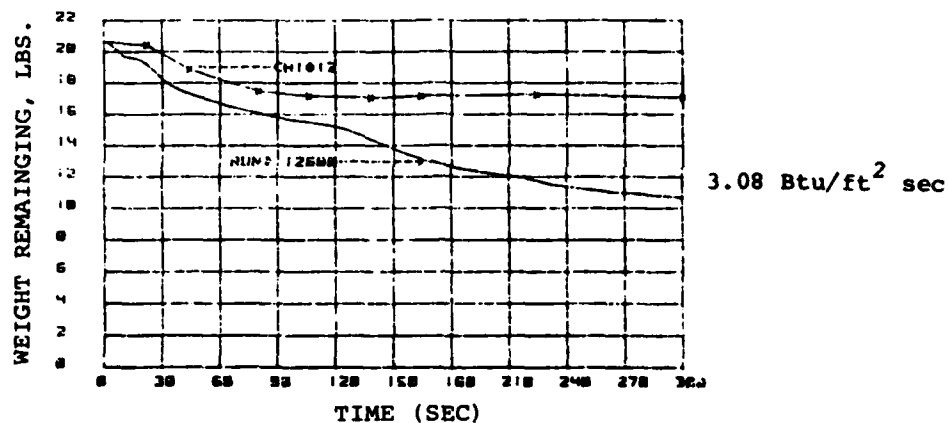
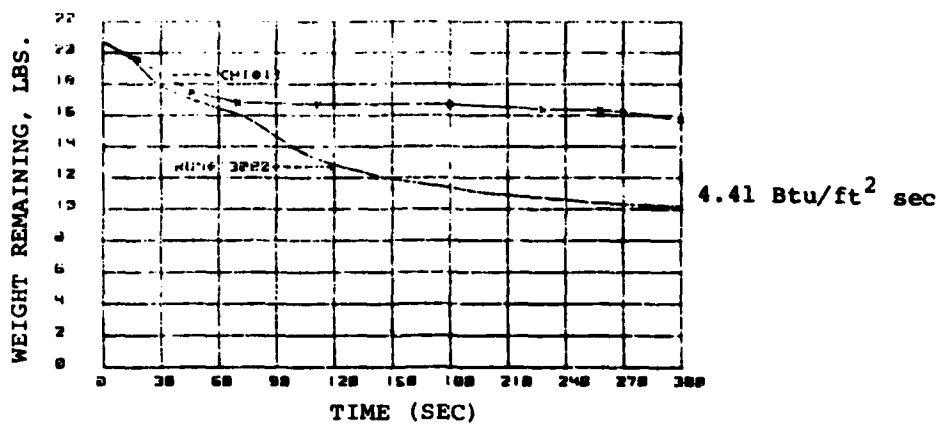


FIGURE 42. COMPARISONS OF CHAS AND CFS WEIGHT LOSS BURN PROFILES OF PANEL 4 MATERIAL (*-* = CFS TEST; — = CHAS TEST PLOT CALCULATED FOR PANEL SIZE USED IN CFS TESTS)

A comparison of the burn profiles of panels 2, 3 and 4, exemplified by the CFS chamber pressure changes recorded during a test, with the hazards release profile patterns in Figures 25-28 showed the following similarities and differences. The CFS pressure peaks and times of occurrence listed in column 6 of Table 15 were used in this comparison. As shown, Panel 2 at lower heat flux showed a major peak at 77 seconds into the burn in the CFS. This was also observed in the CHAS, but at an earlier time. Similar time delays were noted at higher heat fluxes with the appearance of a second peak of lesser intensity at a later time (back side fire involvement). Multiple peaks (3 or more) characterized the hazards release patterns for Panels 3 and 4 with successive peaks diminishing in intensity at later times. The relative intensities of the pressure peaks observed in the CFS tests were much lower than would have been expected from the combined affects of the gases, smoke and heat peaks exhibited in the CHAS tests. These differences correlate with the observed mass burning rate differences.

Table 16 compares the 10 minute CFS exhaust quantities (in grams) of the reactive gas species evolved by panels 2, 3, and 4 with the quantities predicted by the CHAS tests. In most of the runs the quantities of HCL, HF and RCHO collected in 10 minutes were lower than those predicted by the CHAS tests. This was expected since the acid gases (HF & HCL) can react with the CFS steel walls. All of the gases were subject to partial absorption on the smoke particles produced by each test that coated the walls and surfaces inside the CFS. The weight lost by the panel materials in the CFS was (with one exception) lower than the comparable materials burned in the CHAS over the same 300 second burn period. Gas generation rates therefore were less. The radiant panel was operated for the entire 10 minute period in the CHAS tests but was turned off at 5 minutes in the CFS tests. While the burn profiles indicated most of the material consumption occurred in the first 5 minutes, the difference in radiant flux time product would contribute in part to the deviations observed. HCN results were consistently in opposition to the results noted for the other gases. This was found to be caused by a sampling system (HCN monitor) malfunction not discovered until all the CHAS tests were completed.

CFS ANIMAL TESTS - Table 17 separately lists the animal incapacitation results obtained from CFS burn tests of panels 2, 3, and 4. In the first tests of Panel 1, the animals were not adequately shielded from heat generated by the burning material. As a result, it was impossible to tell whether the animals died from exposures to toxic gases, heat, or both. With the redesign of the exposure chambers, using thermally resistant polycarbonate and two inches of fiberglass insulation lined with silicone material inside and metallized silicone outside, thermal protection was greatly improved. As indicated in Table 17, the same number of rats were located in these chambers at the same locations as in previous tests. The three-rat chamber located at the "CHI point" (see Figure 15) was one ft³ in volume (28.32 liter); the other three single rat chambers were 0.26 ft³ (6.45 liter) in volume. Each chamber was ventilated with a diaphragm pump operating at approximately 16 liters/minute. In the first test (CFS, No. 4, Table 15) all of the rat subjects had expired by the time the CFS was cleared of smoke and gases (50 minutes). A repeat run (CFS No. 6) was made at the same heat flux (2.2 Btu/ft² sec) using a new 4 X 6 ft. ceiling Panel (No. 2-4). None of the test animals gave a Ti result and all survived. Two factors, acting together, apparently accounted for the

TABLE 16
COMPARISON OF THE QUANTITIES OF HCN, HCL, HF, AND RCHO PREDICTED BY CHAS TEST RESULTS WITH CFS EXHAUST GAS ANALYTICAL RESULTS FOR A 10 MINUTE TEST PERIOD

CFS TEST NO.	PANEL NO/ HEAT FLUX BTU/FT ² SEC	HCN-G IN 10 MIN		HCL-G IN 10 MIN		HF-G IN 10 MIN		RCHO-G IN 10 MIN	
		PREDICTED BY CHAS	FROM CFS EXHAUST	PREDICTED BY CHAS	FROM CFS EXHAUST	PREDICTED BY CHAS	FROM CFS EXHAUST	PREDICTED BY CHAS	FROM CFS EXHAUST
6	2/2.2	0.20 ①	5.4 ②	-	-	59.8	12.5	5.1	2.8
4	2/2.2	0.20	1.7	-	-	59.8	4.6	5.1	2.8
7	2/3.08	0.20	8.8	-	-	9.7	9.9	4.9	2.6
9	2/4.41	0.33	9.2	-	-	38.6	7.3	1.7	2.0
5	3/2.2	1.81	17.8	747	121	-	-	5.2	4.9
8	3/3.08	1.26	28.6	644	331	-	-	6.2	4.6
10	3/4.41	2.78	25.2	651	351	-	-	4.0	4.7
13	4/2.2	0.77	10.2	265	78.9	114	14.9	7.0	1.6
12	4/3.08	1.20	13.6	410	54.4	127	7.1	3.9	1.0
11	4/4.41	1.58	16.9	415	124.6	120	16.9	3.0	2.0

① CHAS data was calculated from averages of Table 5 and 8 values normalized to panel size used in the CFS tests.

② Calculated from bubbler sampling data - Table 15.

TABLE 17

CFS ANIMAL INCAPACITATION TESTS OF PANELS 2, 3 AND 4 AT THREE HEAT FLUX LEVELS

ANIMAL TEST LOCATION IN CFS ①	ANIMAL NO.	PANEL 2			PANEL 3			PANEL 4		
		2.5 W/CM ² TI SEC MAX °F	3.5 W/CM ² TI SEC MAX °F	5 W/CM ² TI SEC MAX °F	2.5 W/CM ² TI SEC MAX °F	3.5 W/CM ² TI SEC MAX °F	5 W/CM ² TI SEC MAX °F	2.5 W/CM ² TI SEC MAX °F	3.5 W/CM ² TI SEC MAX °F	5 W/CM ² TI SEC MAX °F
MATS IN ZONE 13- "CHI" POSITION 48 IN. ABOVE FLOOR	1	NONE	NONE	NONE	NONE	NONE	685 100 F	NONE	NONE	NONE
	2	NONE	NONE	NONE	NONE	NONE	925 103 F	NONE	NONE	NONE
	3	NONE	NONE	NONE	NONE	NONE	810 101 F	NONE	NONE	NONE
SINGLE CAGE IN ZONE 12 27 IN. ABOVE FLOOR	POST TEST RESULTS	ALL SURVIVED	ALL SURVIVED	ALL SURVIVED	ALL SURVIVED	ALL SURVIVED	#1 SURV'D 2 & 3 DIED	ALL SURVIVED	ALL SURVIVED	ALL SURVIVED
	4	NONE	NONE	2150 91 F	845 82 F	465 94 F	1015 91 F	NONE	2700 88 F	NONE
SINGLE CAGE BETWEEN ZONE 16 & 19 72" ABOVE FLOOR	POST TEST RESULTS	SURVIVED	SURVIVED	SURVIVED	SURVIVED	SURVIVED	DIED	SURVIVED	SURVIVED	SURVIVED
	5	1450 103 F	NONE	1520 88 F	880 90 F	465 94 F	335 109 F	NONE	2750 85 F	3400 90 F
	POST TEST RESULTS	SURVIVED	SURVIVED	SURVIVED	SURVIVED	SURVIVED	DIED	SURVIVED	SURVIVED	SURVIVED
INSIDE "DOOR" NEAR EXHAUST 48" ABOVE FLOOR	6	265-82 F 1250-106 F	NONE	NONE	935 83 F	650 91 F	255 82 F	NONE	2550 88 F	3220 90 F
	POST TEST RESULTS	RECOVERED	SURVIVED	SURVIVED	SURVIVED	SURVIVED	DIED	SURVIVED	SURVIVED	SURVIVED

① Refer to Figure 1

totally different results in these tests. In the first run, the multiple flamelet pilot light did not rotate until 150 seconds into the test. This increased the generation of gaseous decomposition products concentrations at the CHI point (and at other animal test locations) as shown by the relative 2 to 3 times increase in concentrations of HF and RCHO reflected by the analytical results for the bubbler samples taken at the same location. Abnormal temperature was the second factor contributing to the animal fatalities in the first test. Temperatures increased to 115°F inside the test chambers in twenty minutes. This increase was partly caused by heat from the electric pumps which were placed inside the insulation blankets during the first test. All of the animals in this test were alive at the end of 20 minutes, but chamber temperatures increased to nearly 122°F in the following 30 minutes. All subsequent tests were run with successful operation of the pilot light mechanism and with the chamber ventilation pumps mounted outside of the insulation blankets. Thus, Table 17 contains only those animal incapacitation results obtained from the CFS testing of Panel 2, 3, and 4 which was tested with the same procedures employed for the other panel test specimens.

Several aspects of the incapacitation data shown in Table 17 were of interest in evaluation of the significance of the animal test results. First, only one rat (No. 6) experienced a Ti at a time (255 sec) within the 5 minute period the CFS radiant panel remained on. This occurred in testing panel 3 at 4.41 Btu/ft² sec (5 W/cm²). All the other Ti's occurred after the radiant panel was shut down at 320 seconds into the test. Another notable aspect of this test was the relatively low temperature inside the chamber which reached a maximum of 82° F in 1200 sec (20 min). One other animal at the same location appeared to incapacitate at 265 seconds in the low heat flux test of Panel 2. However, this animal continued to walk when the cage rotation was restarted and did not show a more definite Ti until 1250 seconds. The temperature increased to a maximum of 106°F in 20 minutes inside the rat cage chamber in this case. Second, all of the animals showing a Ti either recovered or survived the test except for those used in testing Panel 3 at 4.41 Btu/ft² sec heat flux. Animal No. 5 located 72" above the floor of the CFS midway between the CHI point and the "door" near the exhaust became incapacitated at 335 seconds and was subjected to 109°F in 20 minutes in the panel 3 test at 4.41 Btu/ft² sec. Third, all of the animals in the high flux test of panel 3 incapacitated and only one survived after 50 minutes. The temperature inside the chambers in these tests rose to approximately 122°F in the time interval from 20 to 50 minutes. All of the rats were alive at the end of 20 minutes. Fourth, the apparent ranking of these panels for toxicity hazard by the animals was 2, 4, 3 (in order, least to most toxic) only at 3.08 Btu/ft² sec; at the other heat flux levels the apparent order was 4, 2, 3.

In most of the cases where incapacitation occurred in less than 300 seconds, the temperature appeared to affect the result less than the gases. While the relative contributions of temperature and gases to the Ti was not known, the temperatures holding in the cages at levels of 109-122°F over periods of 20 minutes probably contributed greatly to the observed Ti's.

SINGLE ZONE FACP RESULTS - The single zone FACP calculated the hazards release rates at the CFS exhaust, assuming a well mixed reactor model, using CHAS input data. The program was designed to print out each measured hazard concentration sequentially at selected times. Comparisons and evaluations of the FACP outputs with the hazards measured at the CFS air exhaust were made from computer plots of the FACP data and the measured data.

The independent variables, i.e., effective interior wall surface area of the CFS, wall thermal conductivity, radiant to convective heat ratios, input into the FACP, were adjusted using the temperature comparisons of CFS test data versus FACP predictions. Adjustments of the independent variables in the FACP were made after evaluations of the comparison plots using panel 2 and 3 test results. After the adjustments were complete, panel 4 CHAS data were input into the FACP to demonstrate the capabilities of the program.

Since the CHAS data input to the single zone FACP excluded radiant panel heat, the FACP temperature plots also excluded the CFS radiant panel heat contributions in the comparison evaluations of panels 2, 3 and 4. Another reason for setting the CFS radiant panel heat to zero in the FACP was to calculate the CHI (escape times) based only on the heat released from the materials. The temperature plots for the CFS exhaust air included the radiant panel contributions. Table 18 summarizes the temperature comparisons between FACP outputs and the thermocouple measurements obtained in the tests at the CFS air exhaust.

TABLE 18

COMPARISON OF CFS EXHAUST AIR AND
SINGLE ZONE FACP TEMPERATURES

PANEL NO./ HEAT FLUX, BTU/FT ² -SEC	TEMPERATURE DIFFERENCES AT 90 SEC				TEMPERATURE DIFFERENCES AT 300 SEC			
	CFS EXHAUST °F (1)	PER FACP °F	CFS - FACP		CFS EXHAUST °F (1)	PER FACP °F	CFS - FACP	
			+ °F	+ %			+ °F	+ %
2/2.2	106	104	+2	+1.9	172	130	+42	+24
2/3.08	128	122	+6	+4.7	186	159	+27	+15
2/4.41	157	153	+4	+2.6	223	194	+29	+13
3/2.2	96	76	+20	+21	294	291	+3	+1
3/3.08	125	89	+36	+29	289	363(2)?	-74?	-26?
3/4.41	209	147	+62	+30	326	473	-147	-45
4/2.2	134	108	+26	+19	183	162	+21	+11
4/3.08	156	143	+13	+8	202	255	-53	-26
4/4.41	175	155	+20	+11	242	288	-46	-19

FOOTNOTES: (1) Recorded CFS exhaust air temperatures corrected to same baseline (70°F) at the beginning of each run.

(2) Oxygen consumption instrument malfunction - estimated temperature.

As noted in Table 18, the FACP and CFS exhaust air temperatures were made after correction for the ambient temperature prevailing in the CFS at the beginning of each test run. The beginning temperature for each FACP run was set arbitrarily at 70°F while the CFS start temperatures varied from 80 to 90°F. These baseline differentials were subtracted from the exhaust air temperatures recorded during each run in making the comparisons listed in Table 18. Similar corrections were made in plotting the CFS temperature curve in Figures 43 and 44. These plots are representative of the range of differences between temperatures predicted by the FACP and the actual temperatures measured in the CFS for the "known" panel materials 2 and 3 after adjustment of the independent variables. As shown in the plot comparisons, temperature increases calculated by the FACP and the exhaust temperatures track closely in the first 90 to 120 seconds. Exceptions included two test runs of panel 3 (temperature deviations of +36°F and +62°F, Table 18) and the 2.2 Btu/ft² sec run of panel 4 (with a temperature deviation of +26°F). Up to the standard aircraft cabin emergency escape time (90 sec), the single zone exhaust temperature computer projections correlated satisfactorily with the CFS measurements. After 90 to 100 seconds greater temperature differentials were observed as reflected in Table 18. The positive or negative temperature differentials (+°F, columns 4 and 8), indicate a measure of the accuracy of the temperatures calculated by the single zone FACP. The figures listed in columns 5 and 9 express the differential temperature as a percent by which the CFS exhaust air temperature was either higher (+%) or lower (-%) than calculated by the single zone FACP. In most of the tests the CFS exhaust temperatures were higher than those calculated by the FACP. The exceptions (FACP calculated temperatures higher than measured in the CFS) included the 3.08 and 4.41 Btu/ft² sec runs of panels 3 and 4.

These cases of apparent overprediction by the FACP were not numerically evaluated by a sensitivity analysis of the input variables affecting temperature in the CFS. Air temperature in the CFS was effected by the complex interaction of the radiant and convective heating of the air and chamber walls by both the fire and the radiant source as well as the flow dynamics. However, the observed cases of delta temperature reversals was most probably due to differences in mass burning of the panel materials in the CHAS as compared to the CFS.

As shown by the weight remaining plots in Figure 41, the wood faced panel 3 burned more completely in the CHAS than in the CFS, both in the 3.08 and 4.41 Btu/ft² sec tests. The lower CFS mass burning rate appears to correlate with the lower CFS exhaust air temperature measurements. This is also consistent with the smaller temperature differentials reflected by Table 18 and the nearly identical mass burning rates shown in Figure 41 for the low heat flux run of panel 3.

The above explanation of differences in fire response in the CHAS and the CFS appear to be valid also for panel 4 tests at the two higher heat fluxes as shown in Figure 42 and the temperature differentials in Table 18, but does not account for the converse behavior at the lowest heat flux.

In the panel 2 tests the material contributed considerably less heat to the CFS environment. Figure 40 shows that the mass burning rates for this panel material in the CHAS still were greater than in the CFS, but with less difference than in the other panel tests. The CFS exhaust air temperature listed in Table 18 were slightly higher, in contrast to the cases involving

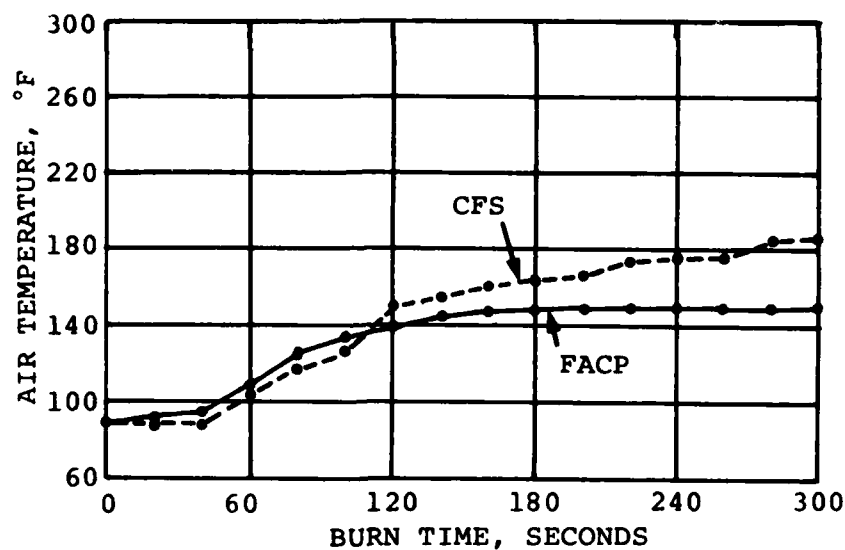


FIGURE 43. COMPARISON PLOTS OF CFS EXHAUST TEMPERATURES CALCULATED BY 1 ZONE FACP AND BY DIRECT MEASUREMENT--PANEL 2 AT 2.2 Btu/ft² sec.

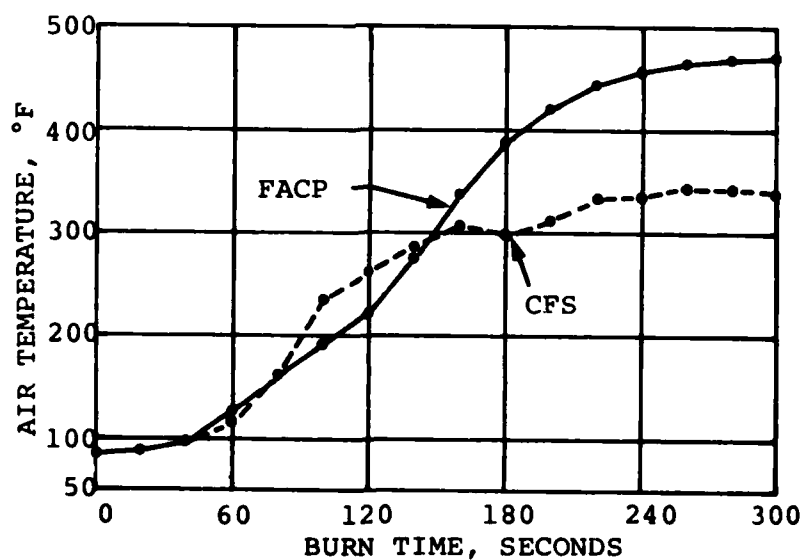


FIGURE 44. COMPARISON PLOTS OF CFS EXHAUST TEMPERATURES CALCULATED BY 1 ZONE FACP AND BY DIRECT MEASUREMENT--PANEL 3 AT 3.08 Btu/ft² sec.

panels 3 and 4, discussed above.

Panel 4 temperature plots are shown in Figure 45. Considering all of the experimental variables affecting tests of the smaller samples with the CHAS and those associated with the larger samples in the CFS, the temperature plots showed reasonable agreement.

Comparison plots of the CFS exhaust combustion products concentrations with the FACP outputs over the 5 minute burn period are shown in Figures 46 through 52. These plots show differences of greater magnitude than those for temperature, with the exception of oxygen depletion (Figure 48), which was not very pronounced in the CFS by the FACP calculation. The changes in oxygen concentration were small because of the large volume of air present in the CFS at the beginning of the test and the relatively low ratios of combustion gas products to air as a material burned. Oxygen was constantly replenished also by the constant airflow pumped into the CFS during these tests. The single zone FACP assumed that all combustion gases were completely mixed with the volume of air present in the CFS extending over the period of the burn test. The experimental plots of CFS CO₂, CO, HCN, CH_x, and smoke demonstrated that concentrational waves of products streamed from the fire to the exhaust due to incomplete mixing with the CFS air, unlike the condition assumed by the FACP calculations. The divergence in the comparisons for CO₂ and CO was due in part to differences in mass burning rates of materials burned in CHAS and in the CFS.

Large deviations were noted in the FACP/CFS comparison plots for HCN. The data processing and plotting was done after all experimental burn testing had been concluded. Later inspection of the sampling system revealed that the HCN detector sampling line had been partly pulled out of a fitting. This was not discovered since this line was covered with heating tape and insulated. The air leak at this point was the main cause for the deviations.

Figures 49, 50, and 51 show plots of the single zone FACP optical transmission calculations (based on CHAS data), decreasing with smoke concentration buildups compared with smoke photometer optical transmission plots near the CFS exhaust during full scale tests of panel 4. The time delay exhibited by the CFS smoke photometer curves in these plots was caused by the flow dynamics in the CFS. Comparison with the TC temperature data recorded at the smoke photometer location (Zone 16, near the exhaust) showed a time lag of 20 to 40 seconds from the start of the test run (0 time), depending on the heat flux employed.

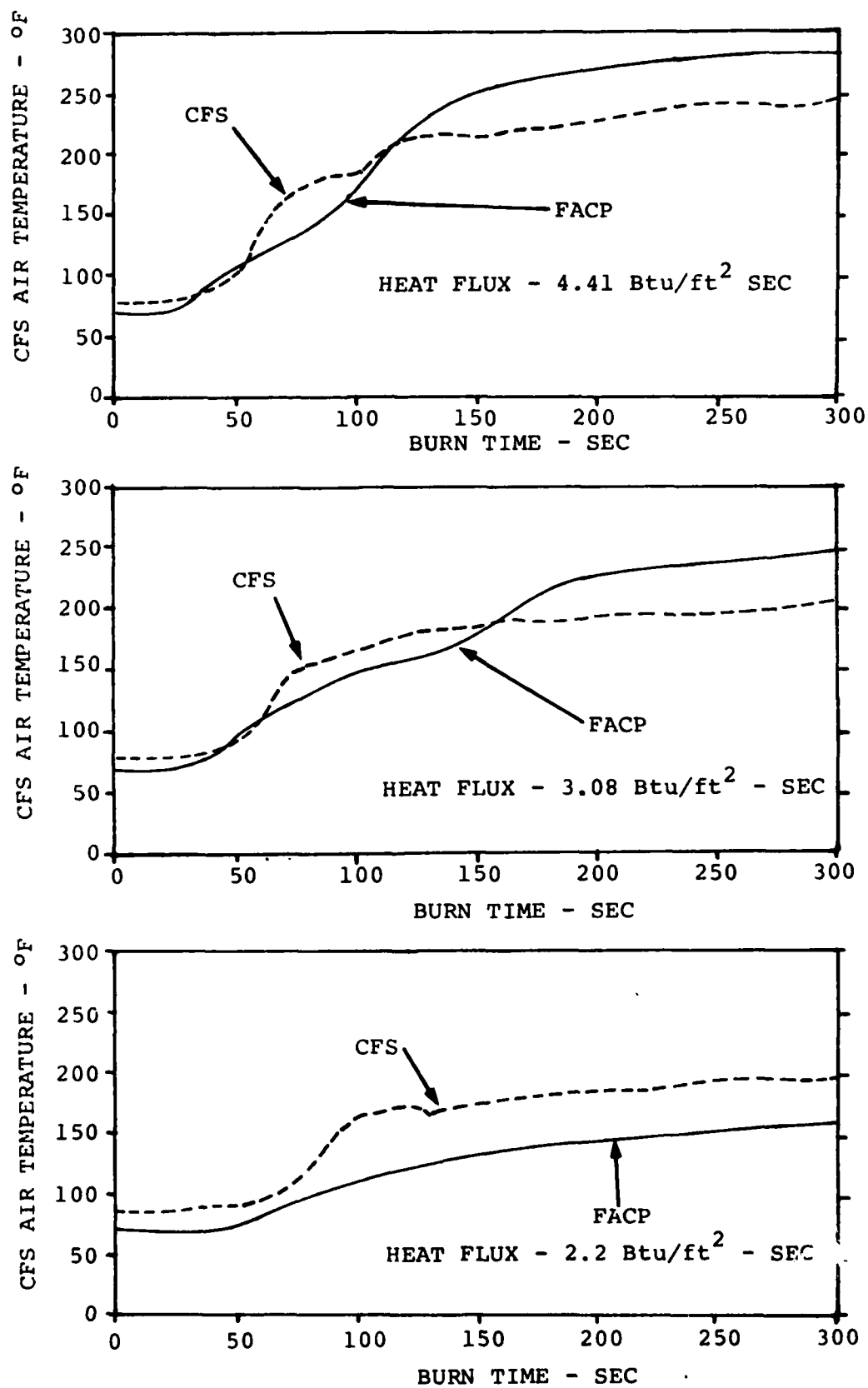


FIGURE 45. COMPARISON OF CFS EXHAUST TEMPERATURES PREDICTED BY THE SINGLE ZONE FACP WITH DIRECT TC MEASUREMENTS PANEL 4 TESTED AT 3 HEAT FLUXES

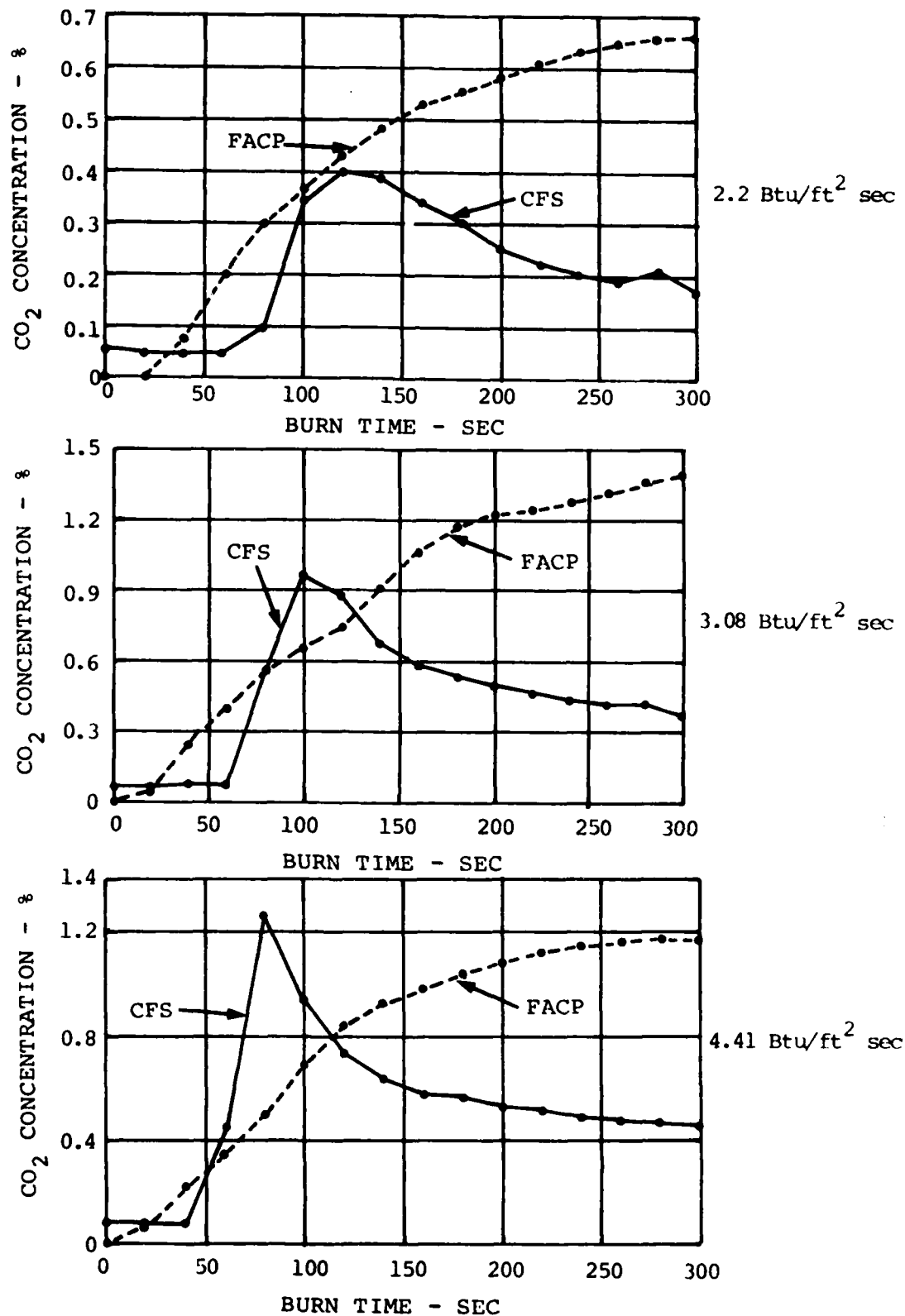


FIGURE 46. COMPARISON PLOTS OF CFS EXHAUST CO₂ CONCENTRATIONS WITH FACP RESULTS - PANEL 4 AT 3 HEAT FLUX TEST LEVELS

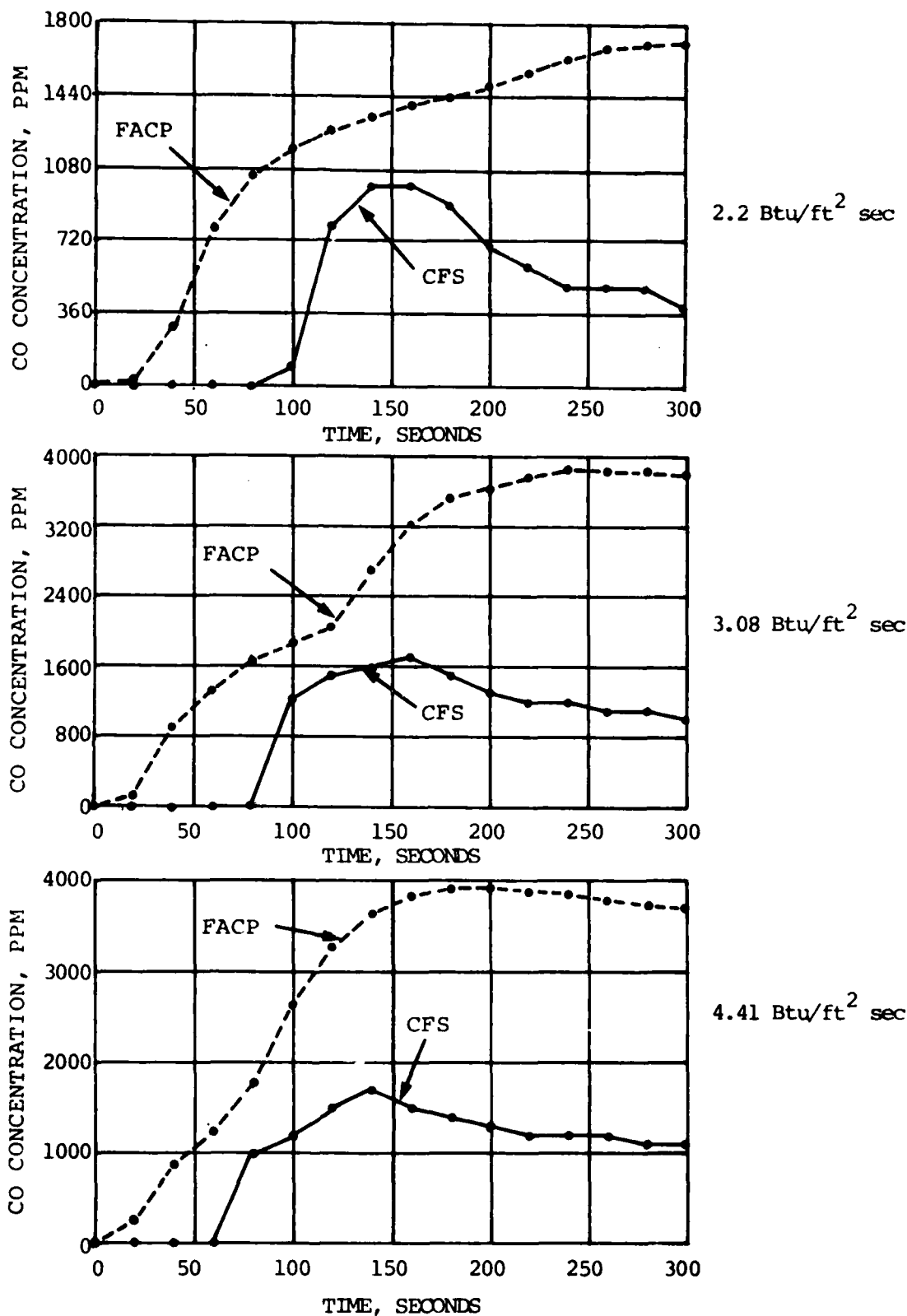


FIGURE 47. COMPARISON PLOTS OF CFS EXHAUST CO CONCENTRATIONS WITH FACP RESULTS FOR PANEL 4 AT 3 HEAT FLUXES

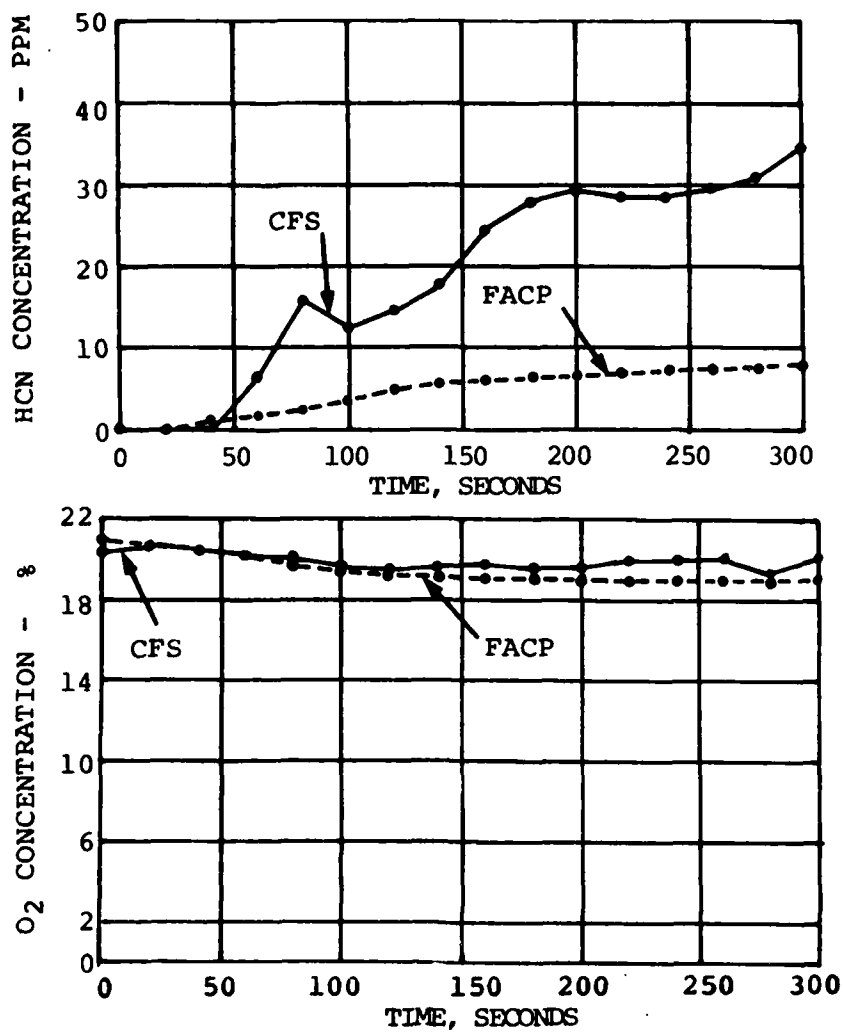


FIGURE 48. COMPARISON PLOTS OF CFS EXHAUST HCN AND O₂ CONCENTRATIONS WITH FACP RESULTS FOR PANEL 4 AT 4.41 Btu/ft² SEC

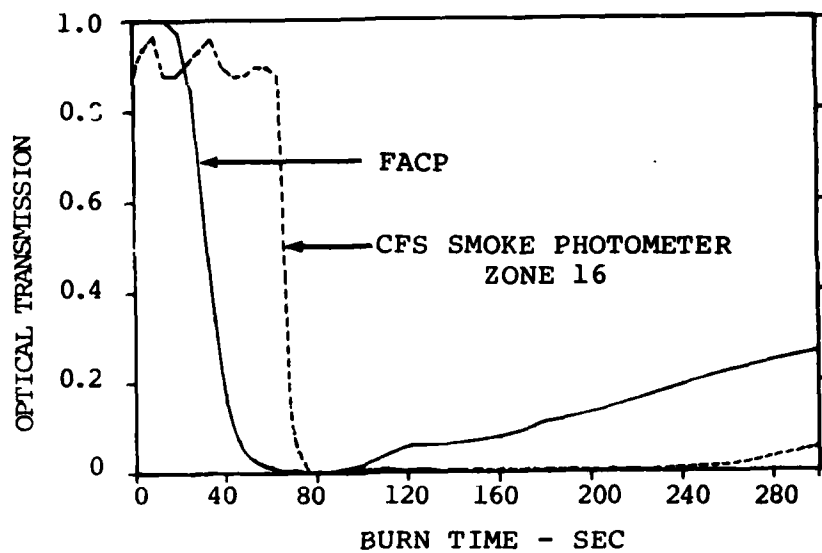


FIGURE 49. COMPARISON OF SMOKE EVOLUTION PROFILES -
SINGLE ZONE FACP PREDICTION WITH CFS
EXHAUST READINGS FOR PANEL 4 AT
3.08 Btu/ft² SEC

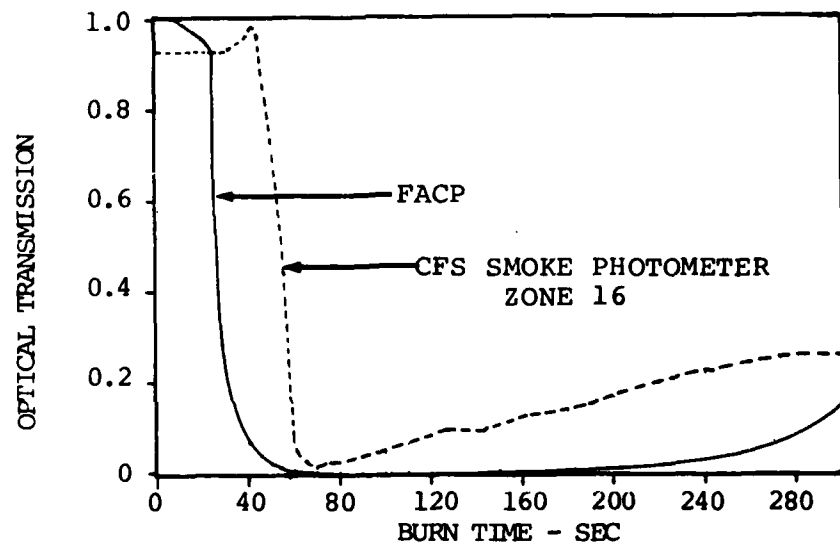


FIGURE 50. COMPARISON OF SMOKE EVOLUTION PROFILES -
SINGLE ZONE FACP PREDICTION WITH CFS
EXHAUST READINGS FOR PANEL 4 AT
4.41 Btu/ft² SEC

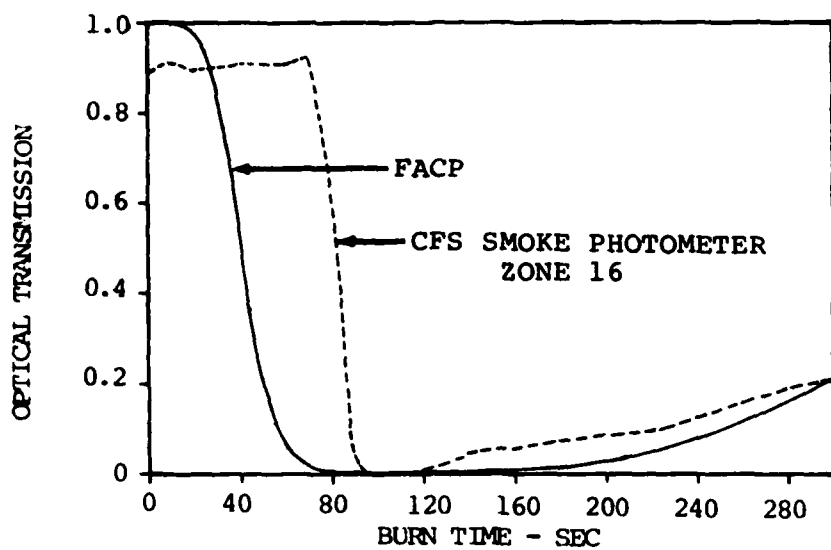


FIGURE 51. COMPARISON OF SMOKE EVOLUTION PROFILES - SINGLE ZONE FACP PREDICTION WITH CFS EXHAUST READINGS FOR PANEL 4 AT 2.2 Btu/ft² SEC

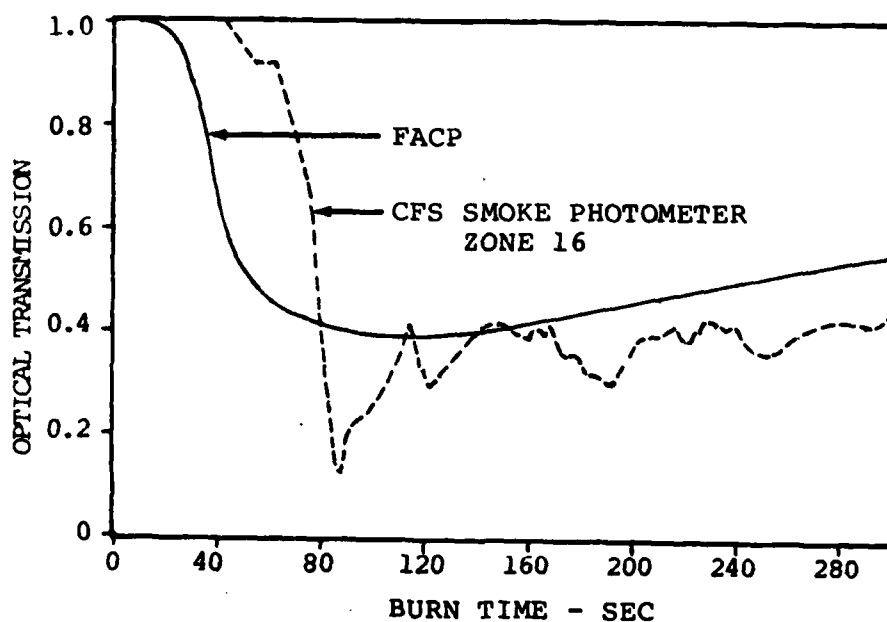


FIGURE 52. COMPARISON OF SMOKE EVOLUTION PROFILES - SINGLE ZONE FACP PREDICTION WITH CFS EXHAUST READINGS FOR PANEL 2 AT 2.2 Btu/ft² SEC

Time delays were not output by the single zone FACP because of the well-mixed reactor assumption. If the photometer plots are shifted by eliminating the time lag in each case, agreement between the predicted and measured transmission curves is fairly satisfactory for 120 seconds of the burn time; less so beyond that time. Figure 52 compared the plots for a lower smoke evolution material (panel 2). Again, the agreement is satisfactory if delay time and the insensitivity of the single zone FACP to flow dynamics is taken into account.

CHI AND SINGLE ZONE FACP FRACTIONAL DOSES - All of the panel materials CHAS data on IBM tape were input and run using the single zone FACP. The individual hazards concentrations evolved and the corresponding "effective" fractional doses were printed out at 5 second intervals over a 300 second burn time. The output data were also stored on disk for transfer to a PDP-11 computer which was used to plot the CHI and fractional dose curves for air temperatures, smoke and materials gaseous combustion products.

FD plots were made at each of three heat flux test levels for panel materials 2, 3, and 4 in addition to one plot of panel 1 at 4.41 Btu/ft²sec. These FD/CHI plots are presented in Figures 53 through 62. In each plot the burn time at which the sum of the hazards FD's equals one is shown ($\sum FD_i = 1$). This time, by definition, is the CHI or relative escape time for 24 square feet of each material burned at three radiant heat fluxes in a 3500 ft³ chamber simulating an aircraft cabin section 12 ft. in diameter and 40 ft. long. The computer program was iterated beyond the CHI point and printed out hazards FD's up to 300 seconds to aid in evaluating the contributions of each hazard FD to the CHI number. The FD values for each hazard at 300 sec were of interest and determined a factor expressing the number of times the mixture incapacitation dose was exceeded at the scenario time limit.

The plots are largely self-explanatory. However, the following observations are of importance in evaluating the fire hazards evolution response of the test panels. Certain deviations from expected results have rational explanations and give additional confidence that the CHI methodology can yield a reasonably accurate relative hazards ranking if proper test procedures are followed. One would expect that most of the combustion products evolution rates would increase in a somewhat regular manner (within certain limits) with increasing fire threat levels (radiant heat flux). Some materials combustion products of a more labile or chemically reactive nature may decrease in concentration with higher external heat flux. Readily oxidizable species such as CO, CH_x, HCN, and aldehydes (RCHO) fall in the latter category.

Comparisons of the FD plots of CHI, smoke and gases for panel 2 at 3 different radiant heat flux test levels shows some of these variations. With increasing heat flux, the FD curves for air temperature, smoke, and most of the other hazards increase (steeper slope and higher FD value), as shown in Figures 54, 55, and 56. The most notable exception to this was HF at 3.03 Btu/ft² sec (Figure 55). The slope of the HF plot in this case was lower than the corresponding plot in the 2.2 Btu/ft² sec (Figure 54). Since HF is a principal driver in determining CHI, the inference is that panel 2 was less hazardous at 3.08 than at 2.2 Btu/ft² sec. A review of the timing sequence used for the HF syringe batch sampling required for this run (CHAS) showed that the first syringe sample was not taken until 1 minute into the burn. Thus, the first peak evolution of HF was missed and the resulting FACP FD plot was lower

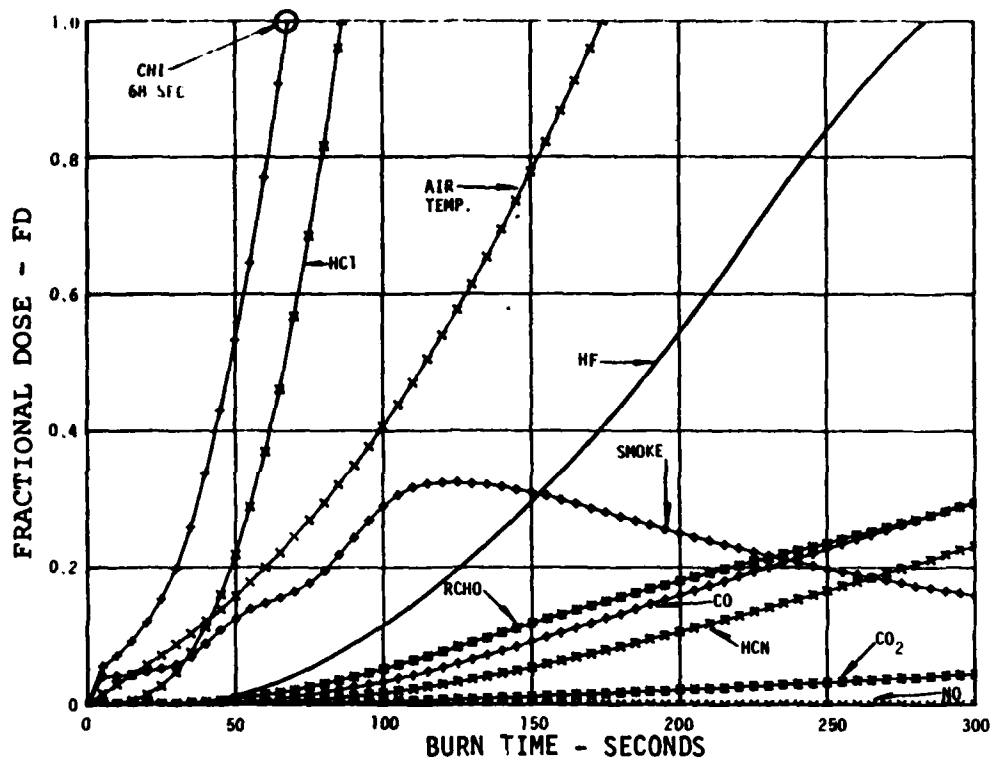


FIGURE 53. SINGLE ZONE FACP CHI AND FRACTIONAL DOSE PLOTS - PANEL 1 AT 4.41 Btu/ft² sec

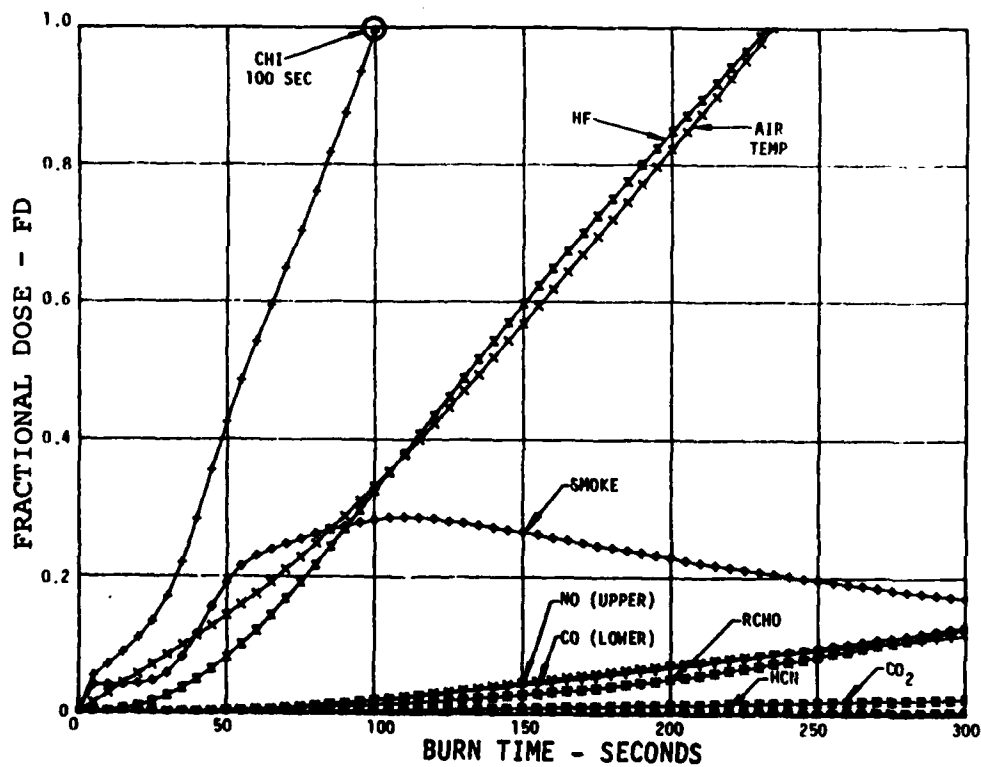


FIGURE 54. SINGLE ZONE FACP CHI AND FRACTIONAL DOSE PLOTS - PANEL 2 AT 2.2 Btu/ft² sec

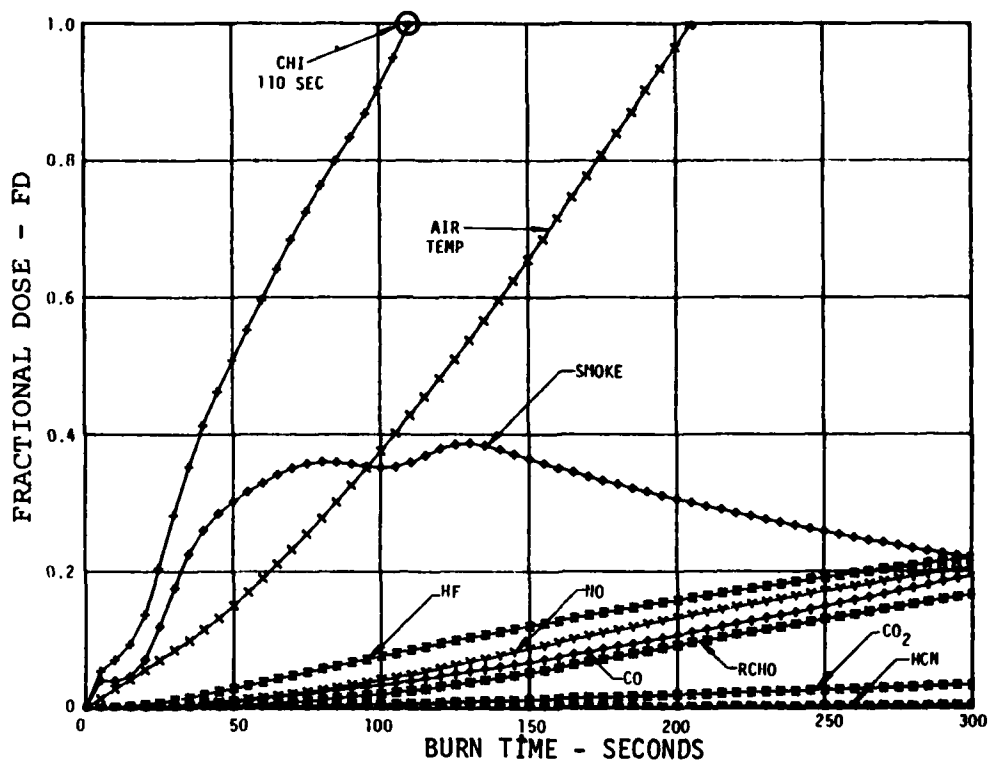


FIGURE 55. SINGLE ZONE FACP CHI AND FRACTIONAL DOSE PLOTS - PANEL 2 AT 3.08 Btu/ft² sec

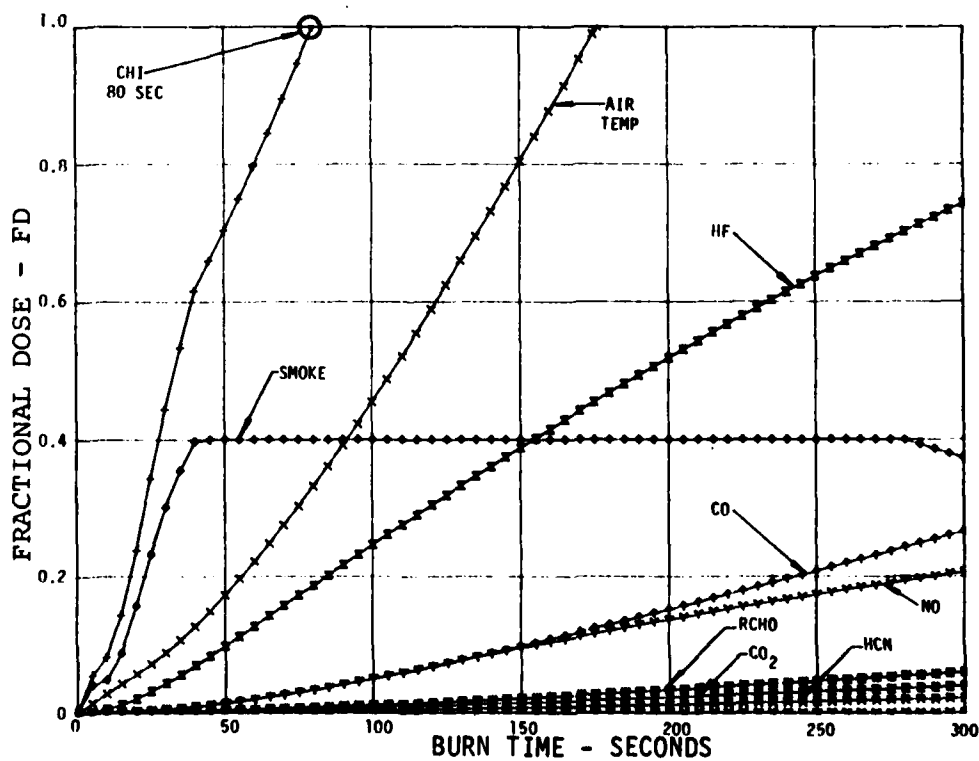


FIGURE 56. SINGLE ZONE FACP CHI AND FRACTIONAL DOSE PLOTS - PANEL 2 AT 4.41 Btu/ft² sec

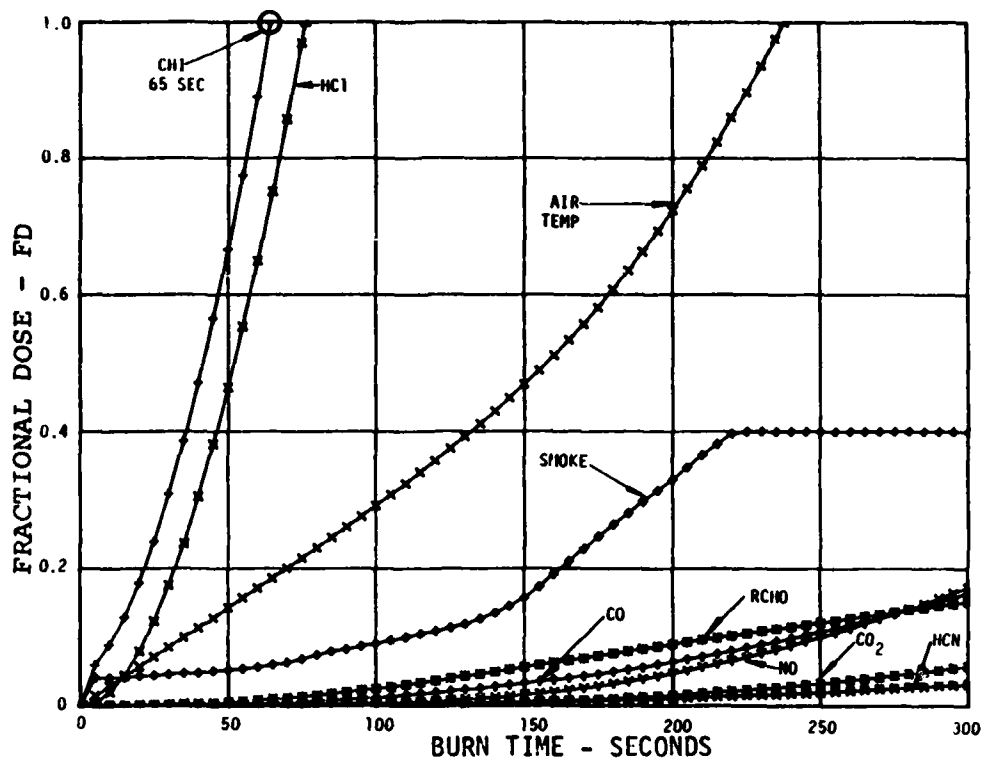


FIGURE 57. SINGLE ZONE FACP CHI AND FRACTIONAL DOSE PLOTS - PANEL 3 AT 2.2 Btu/ft² sec

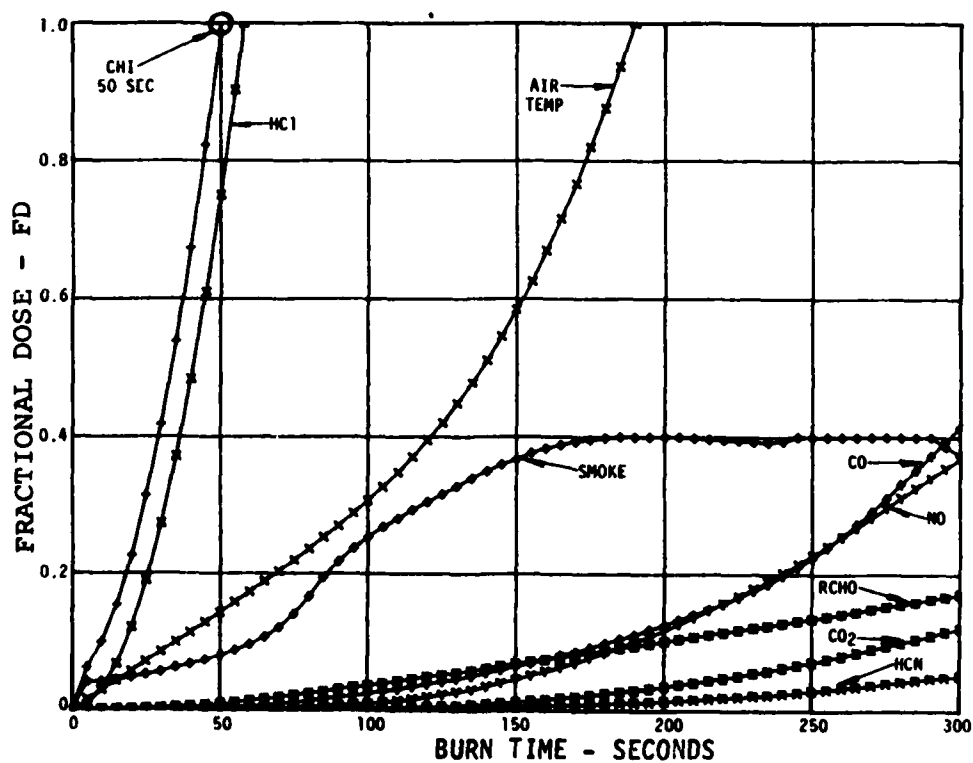


FIGURE 58. SINGLE ZONE FACP CHI AND FRACTIONAL DOSE PLOTS - PANEL 3 AT 3.08 Btu/ft² sec

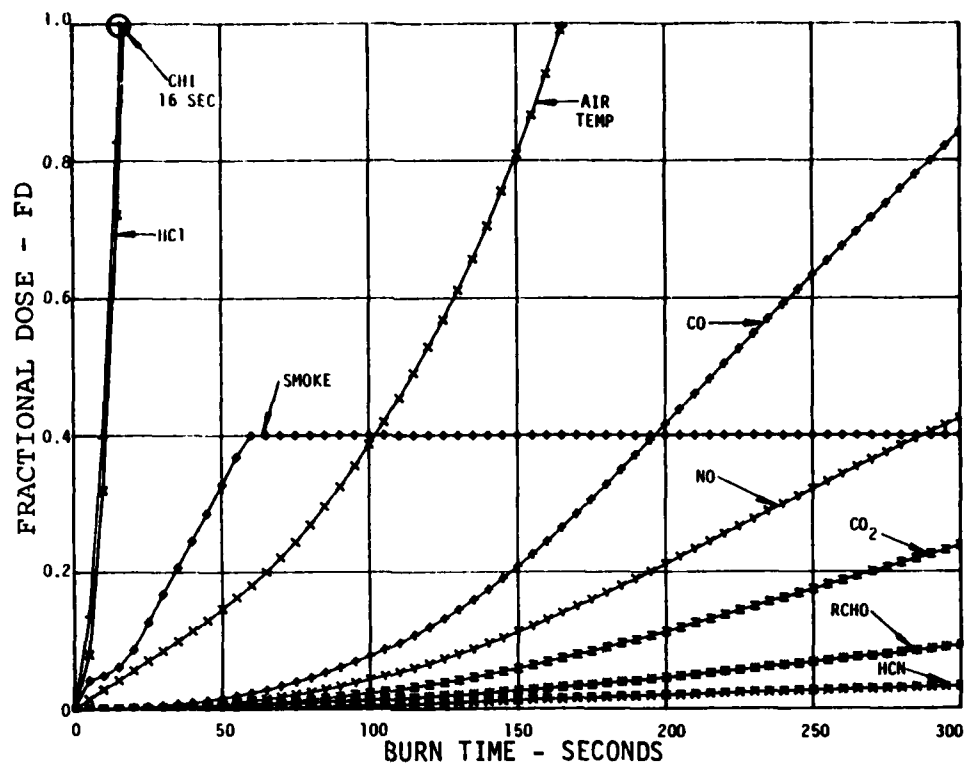


FIGURE 59. SINGLE ZONE FACP CHI AND FRACTIONAL DOSE PLOTS - PANEL 3 AT 4.41 Btu/ft² sec

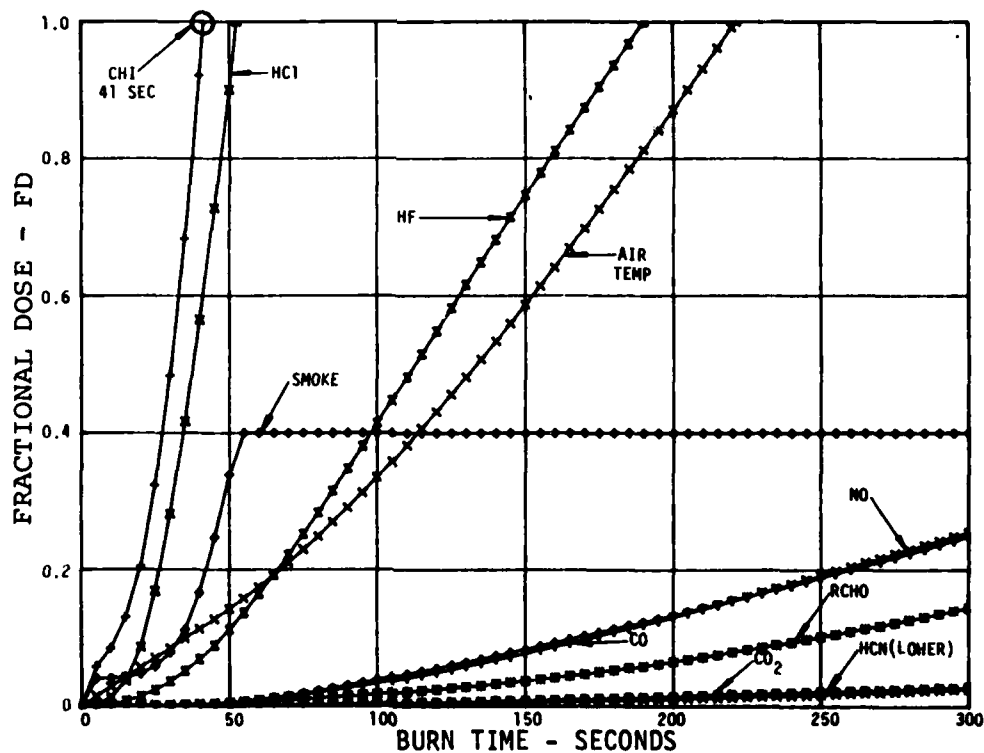


FIGURE 60. SINGLE ZONE FACP CHI AND FRACTIONAL DOSE PLOTS - PANEL 4 AT 2.2 Btu/ft² sec

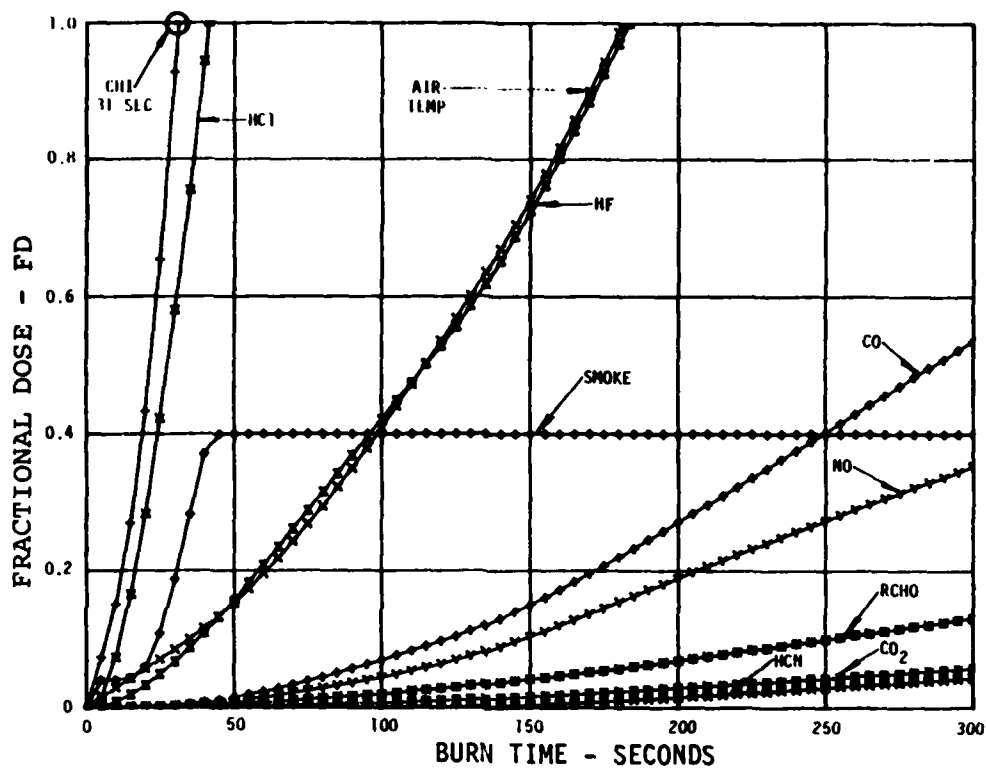


FIGURE 61. SINGLE ZONE FACP CHI AND FRACTIONAL DOSE PLOTS - PANEL 4 AT 3.08 Btu/ft² sec

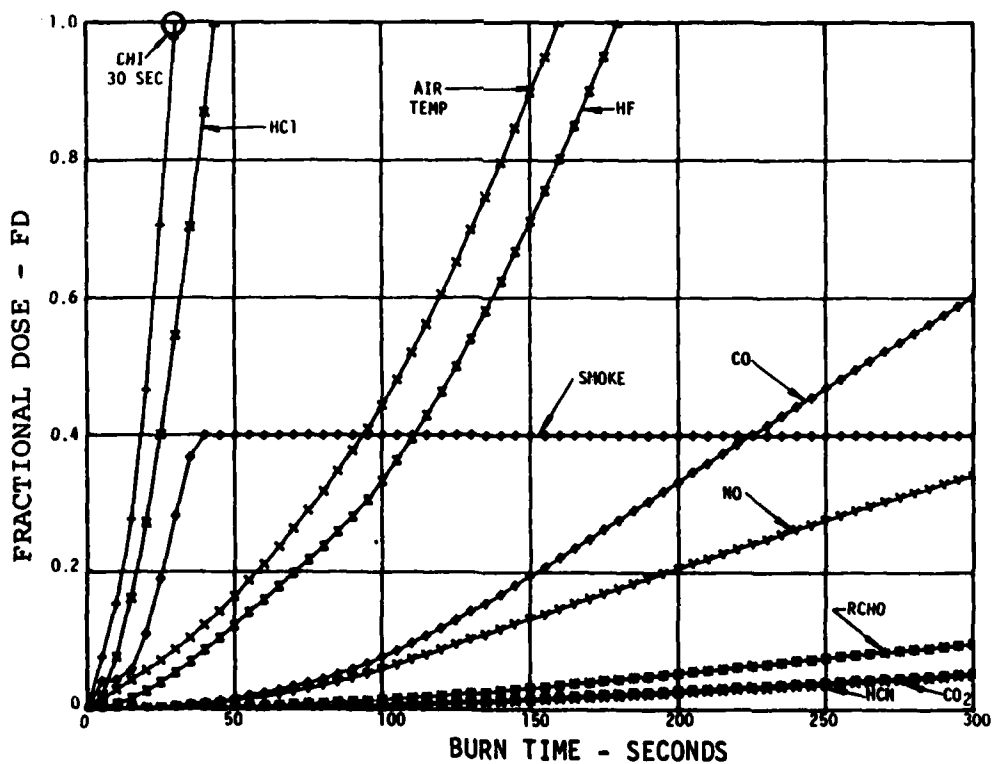


FIGURE 62. SINGLE ZONE FACP CHI AND FRACTIONAL DOSE PLOTS - PANEL 4 AT 4.41 Btu/ft² sec

because of this sampling error. The FD curve for HF in the 3.08 heat flux run would have plotted with a slope between the 2.2 and 4.41 runs and, as an estimate, the CHI should have been near 90 instead of 110 seconds.

A uniform syringe batch sampling timing regime was adopted thereafter which permitted taking more samples earlier in the burn tests. The FD HCl curve slopes and intercepts with the FD limit correlated much better with other hazards generation rates and the CHI values for panels 3 and 4.

It was noted that CO and NO increased with heat flux while RCHO decreased. The increase in CO would not normally be expected since the tests in the CHAS were not considered to be deficient in oxygen due to the airflow setting. A decrease in CO concentration would normally result in an increase in the CO₂ concentration. However, most of the panel runs at higher heat flux showed a persistent smoldering reaction. This occurred in the aramid honeycomb cores in panels 1, 2, and 4, and in the wood of panel 3 which increased the CO in the combustion product stream after the peak burning phase.

TWENTY ZONE FACP CHI AND FRACTIONAL DOSE RESULTS - The 20 zone FACP calculated and printed out the fractional doses and changes in air temperature, smoke, and gas concentrations evolved into each of the 20 zones, dividing up the internal volume of the CFS at 5 second intervals, from 24 ft² panel materials. The data input to the 20 zone FACP was derived from CHAS tests on smaller size panel materials tested at 3 different heat fluxes, as with the single zone FACP. In addition to the hazards, the rate of change of air temperature dT/dt, wall temperature (bounding part of a zone), radiant heat input and total pressure were printed out for each 5 second interval. Twenty nine parameters were printed out for each zone for a run time of 300 seconds. Each computer run printed out 34,800 data points describing the fire response of a material.

Because of CHI program cost constraints the 20 zone FACP was run for demonstration panel 4 at all heat flux test levels and only at the highest heat flux for panels 1, 2, and 3. Table 19 lists hazards evolution values printed out for the 13th zone (CHI location), calculated by the 20 zone FACP for Panel 4. These values are compared in the table with those measured at the same time during the CFS full-scale tests by calculation of the difference in the readings. The listed CFS temperatures above 70°F were not corrected to account for the difference in temperatures in the CFS at the start of each full scale test. The FACP was initialized to 70°F while the low, medium and higher radiant flux tests of panel 4 began with CFS ambient temperatures of 88.9, 83.1, and 80.3°F, respectively, and are included in the CFS measurements and contributed to the nominal differences listed in Table 19.

The nominal temperature deviations between the 20 zone FACP calculations and the TC measurements in the 13th zone, during the first 120 seconds of the CFS burns at 2.2 and 3.08 Btu/ft² sec, exceeded those at 4.41 Btu/ft² sec. It appeared that the more rapid heat release from the material in the CHAS in the first 120 or 150 seconds resulted in higher FACP temperature calculations for zone 13 than the temperatures actually measured in the CFS tests of panel 4. This would have been favored by the higher mass burning rate in the CHAS. The CHAS data input and calculations of the 20 zone FACP included only the radiant and convective heating of CFS air and walls resulting from the heat released by the burning panel, modified by the flow dynamics in zone 13. After 120 or 180 seconds, the panel material flaming and heat release subsided. As indicated in Table 19, the FACP predicted that air temperatures reached a peak near 90 or

TABLE 19
COMPARISON OF MEASURED HAZARDS IN CFS ZONE 13 WITH HAZARDS PREDICTED BY
20 ZONE FACP - PANEL 4

BURN TIME SEC	AIR TEMP. °F		OXYGEN %		CO ₂ %		CO %		HCN PPM		HF PPM		HCl PPM		ALDEHYDE PPM	
	FACP	CFS	±	Δ	FACP	CFS	±	Δ	FACP	CFS	±	Δ	FACP	CFS	±	Δ
30	80	79	-1		20.9	20.3	-0.6		0.01	0.05	+0.04	0.006	0	-0.006		
60	125	85	-40		19.7	20.3	+0.6		0.62	0.15	-0.47	0.24	0	-0.24		
90	186	117	-75		18.2	20.2	+1.0		1.64	0.35	-1.29	0.59	0.01	-0.58		
120	183	155	-28		18.5	20.1	+0.6		1.80	1.05	-0.75	0.52	0.39	-0.13		
180	149	169	+20		18.8	19.8	+1.0		1.61	0.65	-0.96	0.34	0.20	-0.14		
240	126	182	+56		19.3	19.9	+0.6		1.26	0.75	-0.51	0.29	0.17	-0.12		
300	116	193	+77		19.5	19.9	+0.4		1.05	0.50	-0.55	0.27	0.15	-0.12		
30	91	79	-12		20.5	20.2	-0.3		0.13	0.05	-0.08	0.04	0	-0.04		
60	230	105	-125		17.3	20.3	+3.0		2.00	0.05	-2.05	0.70	0.01	-0.69		
90	256	147	-109		16.5	20.2	+3.7		2.91	0.55	-2.36	0.85	0.11	-0.74		
120	221	169	-52		17.3	19.9	+2.6		2.82	0.65	-2.17	0.72	0.28	-0.44		
180	271	194	-77		16.0	19.7	+3.7		3.47	0.65	-2.82	1.09	0.19	-0.90		
240	169	202	+33		17.6	19.8	+2.2		2.43	0.6	-1.83	0.73	0.13	-0.60		
300	153	210	+57		18.2	19.8	+1.6		2.09	0.5	-1.59	0.49	0.12	-0.37		
30	115	85	-30		20	20.0	0		0.25	0.05	-0.20	0.09	0	-0.09		
60	155	134	-21		17.2	20.9	+3.7		1.78	0.40	-1.38	0.67	0.03	-0.64		
90	184	183	-1		15.7	20.8	+5.1		2.61	1.55	-1.06	0.90	0.31	-0.59		
120	219	207	-12		13.8	20.6	+6.8		3.46	0.80	-2.66	1.43	0.31	-1.12		
180	124	234	+110		16.5	20.6	+4.1		2.50	0.70	-1.80	1.01	0.21	-0.80		
240	106	242	+136		18.0	20.6	+2.6		1.94	0.55	-1.39	0.56	0.15	-0.41		
300	94	247	+153		18.9	20.7	+1.8		1.60	0.60	-1.0	0.38	0.15	-0.23		

± = CFS Measurement - FACP calculation

120 or 150 seconds at each heat flux, and decreased thereafter. The actual TC measurements of air temperature in zone 13, however, continued to rise slowly to levels higher than those calculated by the FACP, reaching maximum temperatures of 1193, 210, and 247°F at 300 seconds at 2.2, 3.08 and 4.41 Btu/ft² sec, respectively. This positive temperature deviation over FACP calculations may be due to convective heating of cabin air flowing over the hot lamps, reflectors and housings of the radiant source. Thus, if this is true, in terms of the temperature hazard contributed only by the burning material, the FACP gave a more accurate estimate of the air temperature hazard than the CFS measurements.

The differences in oxygen percentages measured in the CHAS and CFS tests were generally consistent with the observed differences in mass burning rates reflected in Figure 42. However, the oxygen consumption differentials can not be directly equated with the temperature differentials. Thus, the +6.8% oxygen consumption differential for the high heat flux run of panel 4 at 120 seconds should have resulted in a large difference in temperature. The temperature difference was only -12°F which may reflect the compensating effect of the CFS radiant source heat.

Large deviations in the CO_2 , CO , HCN , HF , HCl , and aldehyde (RCHO) concentrations ranging from nearly 50 to 90% were found as shown in Table 19. With the exception of HCN , the concentrations calculated by the 20 zone FACP for zone 13 were much higher than the corresponding values measured in the CFS at the same time in a burn test. HCN sampling system leakage in the panel 4 CHAS tests generally account for the positive differences in concentrations as shown in Table 19. The large differences for the other gaseous hazards in comparing CHAS with CFS data are attributable to one or more of the following:

- (1) Mass burning rate differences
- (2) Instrument malfunction or calibration errors
- (3) Sampling errors
- (4) Differences in gas desorptions from or absorptions on CFS walls and other surface reactions
- (5) Microchemical assay errors (HCl , HF , RCHO , HCN)

Errors resulting from (2), (3) and (5) could have caused some of the differences observed, but were not considered major contributors. All of the instruments were carefully calibrated using certified gas concentration mixtures prior to CFS and CHAS tests. Heated Teflon lines were used in the CHAS and except for the HCN monitor line, did not appear to leak. Ten to fifteen ft. teflon lines connected the instruments to the zone 13 sampling location in the CFS. Short lengths of stainless steel tubing connected to the steel solenoid valves in the batch glass bubbler sampling unit (Figure 18) were exposed to gases during a test. Some loss may have occurred in sampling with this unit, particularly with the more reactive acid gases, HCl and HF . None of these sources of error or those of (5) appeared to be great enough to account for such large differences.

(1) and (4) most probably explain the major differences in gas concentrations measured in the CHAS and CFS. The steel CFS walls were exposed to the fire atmosphere and smoke generated by the burns absorbed a portion of each gas. The greatest losses were observed with the more reactive species, HF and HCl . Assay results from the samples taken during full scale testing of panel 3 (wood with PVC facing) showed an evolution of HF . Since this panel material did not include a polymer containing fluorine, the HF must have desorbed from soot collected from previous runs due to heat. A similar desorption was noted in panel 2 tests involving HCl , which was not a product of decomposition of this panel material.

Figures 63 and 64 show a comparison of the 20 zone FACP smoke transmission profiles for zones 13 and 16 with the corresponding smoke photometer profiles for panel 4 tested at $3.08 \text{ Btu/ft}^2 \text{ sec}$. Figures 65 and 66 show a similar comparison for panel 4 at $4.41 \text{ Btu/ft}^2 \text{ sec}$. Zone 16 was near the CFS exhaust. These profiles are similar to those shown for the 1 zone FACP. These profile comparisons indicate that the smoke accumulation rates predicted by the 20 zone FACP were similar to the CFS photometer measured rates, but that the flow coefficients (CA's) were not optimized. The difference in transmission beyond 80 seconds can be ascribed mainly to the mass burning rate difference in the CHAS and CFS. The lag in time between the two profiles, however, appeared to be due to the inability of the FACP flow calculations to entirely account for the intermixing rates of the ceiling smoke layer with the middle atmosphere zones in the CFS.

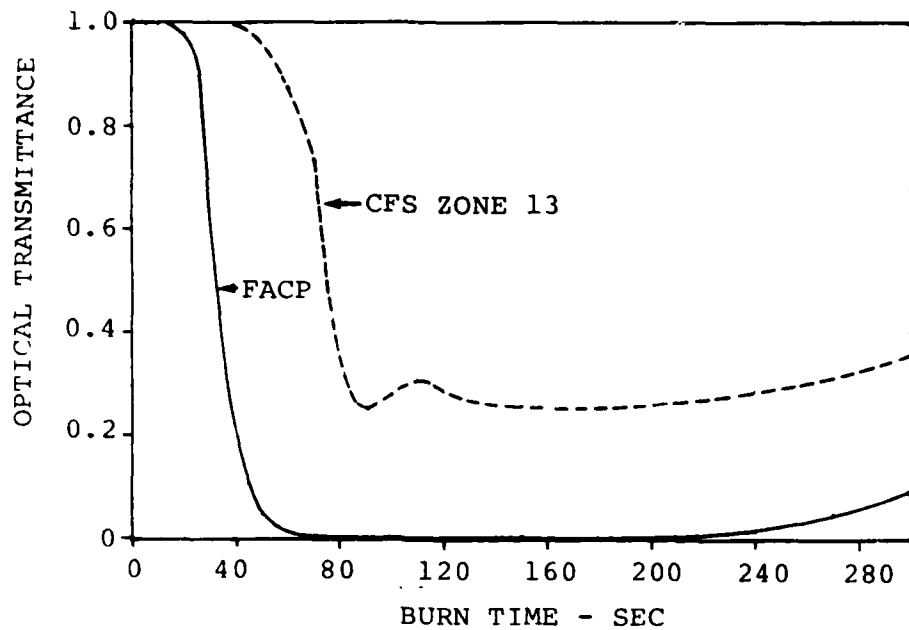


FIGURE 63. COMPARISON OF SMOKE OPTICAL TRANSMITTANCE OF CFS (ZONE 13) WITH 20 ZONE FACP PREDICTION PANEL 4 AT 3.08 Btu/ft² SEC

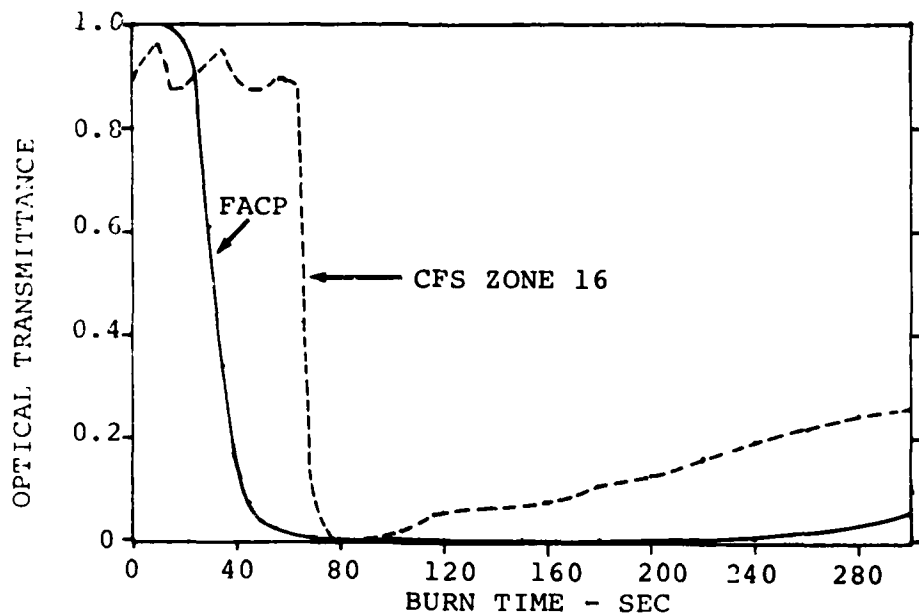


FIGURE 64. COMPARISON OF SMOKE OPTICAL TRANSMITTANCE NEAR CFS EXHAUST (ZONE 16) WITH 20 ZONE FACP PREDICTION PANEL 4 AT 3.08 Btu/ft² SEC

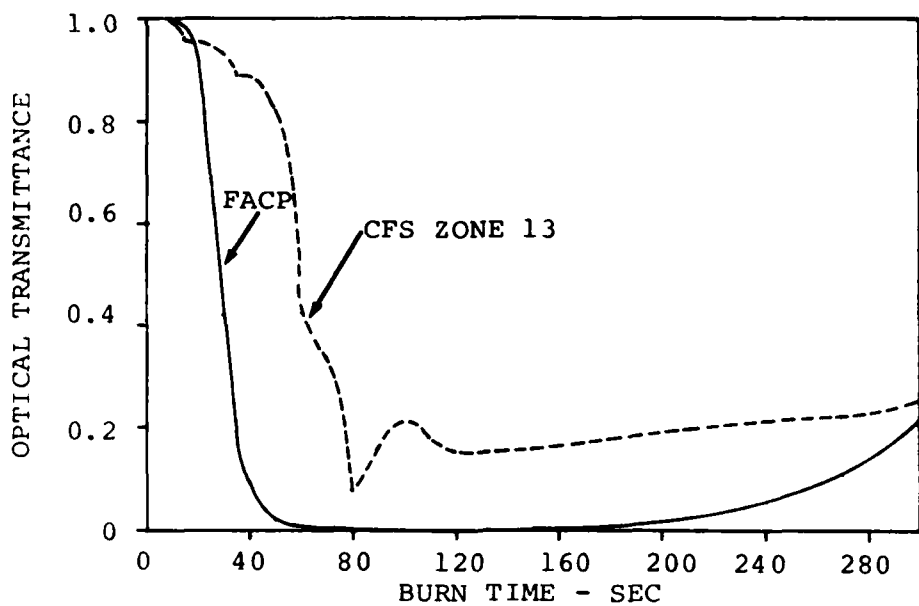


FIGURE 65. COMPARISON OF SMOKE OPTICAL TRANSMITTANCE OF CFS (ZONE 13) WITH 20 ZONE FACP PREDICTION PANEL 4 AT 4.41 Btu/ft² SEC

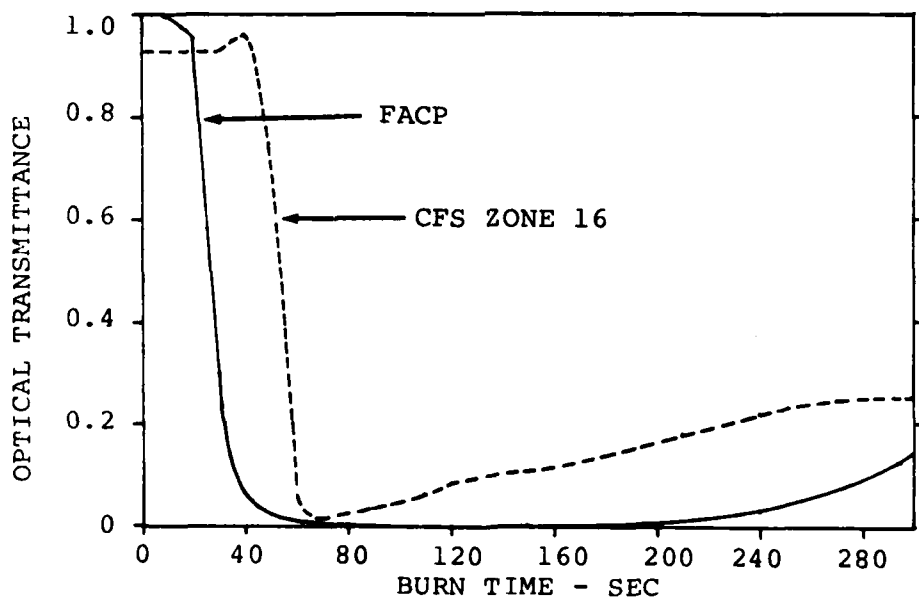


FIGURE 66. COMPARISON OF SMOKE OPTICAL TRANSMITTANCE NEAR CFS EXHAUST (ZONE 16) WITH 20 ZONE FACP PREDICTION - PANEL 4 AT 4.41 Btu/ft² SEC

Figures 67, 68, and 69 compare the calculated 1 zone and 20 zone FACP temperature profiles in the CFS at or near the air exhaust duct (zone 16). These all show more rapid changes in temperature for the 20 zone FACP than for the 1 zone FACP. The latter program assumed instantaneous and complete mixing of the heat generated with the total volume of air in the CFS. The peak contributions of heat therefore were not emphasized in the 1 zone FACP as in the smaller volume of zone 16 where the transport equations in the 20 zone FACP greatly affect the temperature excursions.

For comparison with the 1 zone FACP results, the 20 zone FACP CHI and hazards fractional dose profiles for zone 13 were plotted for panels 1, 2, and 3 at 4.41 Btu/ft² sec and for panel 4 at all heat fluxes. These are presented in Figures 70 through 75. As in the corresponding plots of the single zone FACP, HCl, smoke, air temperature and HF were the strongest drivers affecting the CHI plot. Based on these plots the CHI values at 4.41 Btu/ft² sec for Panels 1, 2, 3, and 4 were 50, 46, 21, and 38 seconds, respectively which corresponds to a ranking relative to increasing hazards of 1, 2, 4, 3. As shown in Figures 73, 74, and 75, the panel 4 CHI values decreased with increasing heat flux.

HAZARDS RATINGS OF THE CHI PROGRAM PANEL MATERIALS

Table 20 summarizes the single and 20 zone FACP CHI relative rankings of panels 1, 2, 3, and 4. In addition to the CHI values (escape time seconds), the number of times the summed fractional doses exceeded unity at 300 seconds are shown for comparison. The rankings listed in the table were determined from the CHI values only. At the highest heat flux test level, both the 1 zone and 20 zone programs ranked panel materials 3 and 4 in the same order.

While the two programs indicated that panel materials 1 and 2 evolved lower hazards than 3 and 4, the ranking order reversed as shown in Table 20. A comparison of the FD plots of these panels in Figures 53 and 70 (panel 1) and Figures 56 and 71 (panel 2), output by the two program versions, indicated that 3 hazards contributed 90 to 95% of the fractional dose summations as shown by the CHI plots. Smoke, air temperature, and acid gases (HF or HCl) were the principal hazards affecting the CHI plot limit in each case. In the 20 zone FACP runs for panels 1 and 2, the smoke FD contribution for panel 2 (Figure 71) appears to have driven the CHI plot to the limit 4 seconds sooner than the CHI limit value for panel 1.

It should be noted that the 1 zone program FDi summations at 300 seconds for panels 1 and 2, tested at 4.41 Btu/ft² sec, were consistent with the CHI relative rankings. The FDi summation for panel 1 at 300 seconds was 22 times greater than its CHI limit, while the 300 sec FDi summation for panel 2 was only 3.7 times greater than its CHI limit. These values correspond with the relative CHI numbers, which showed that panel 1 (68 sec) was more hazardous than panel 2 (80 sec). The 20 zone FACP runs did not show the same consistency since the CHI value for panel 1 (50 sec) indicated it was slightly less hazardous than panel 2 (46 sec) but the corresponding 300 second FDi summations reversed the apparent ranking (55x versus 5.1x). However, for both the 1 and 20 zone programs, the summed fractional effective doses at 300 seconds for panel 1 is much greater than for panel 2.

Very probably the CHI values for panels 1 and 2 are numerically too close to rank them with confidence. The Panel 1 CHAS tests were run during the development phase of the program and the syringe sampling techniques were less

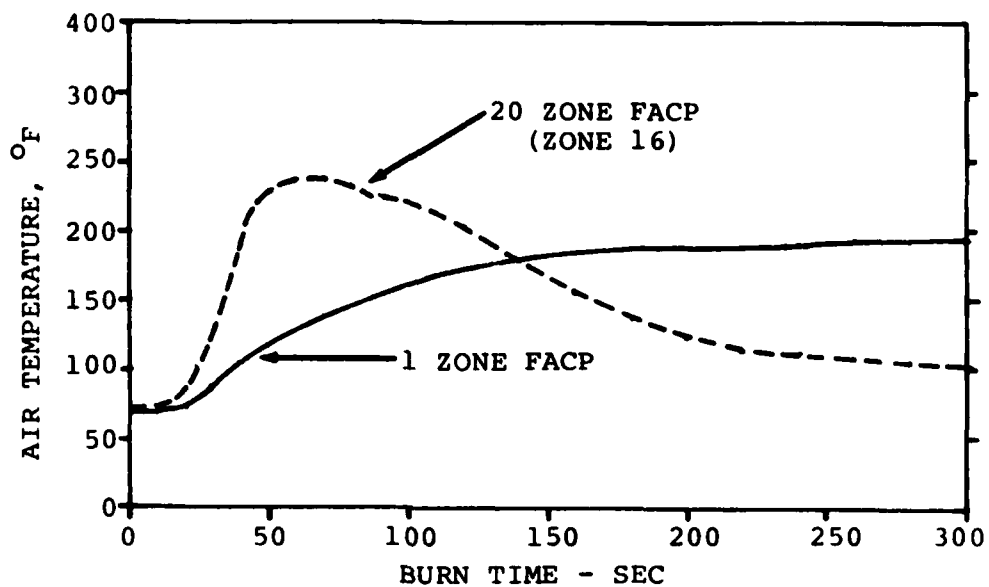


FIGURE 67. AIR TEMPERATURE COMPARISON - 1 ZONE FACP AT CFS EXHAUST AND 20 ZONE FACP AT ZONE 16 PANEL 2 AT 4.41 Btu/ft² SEC

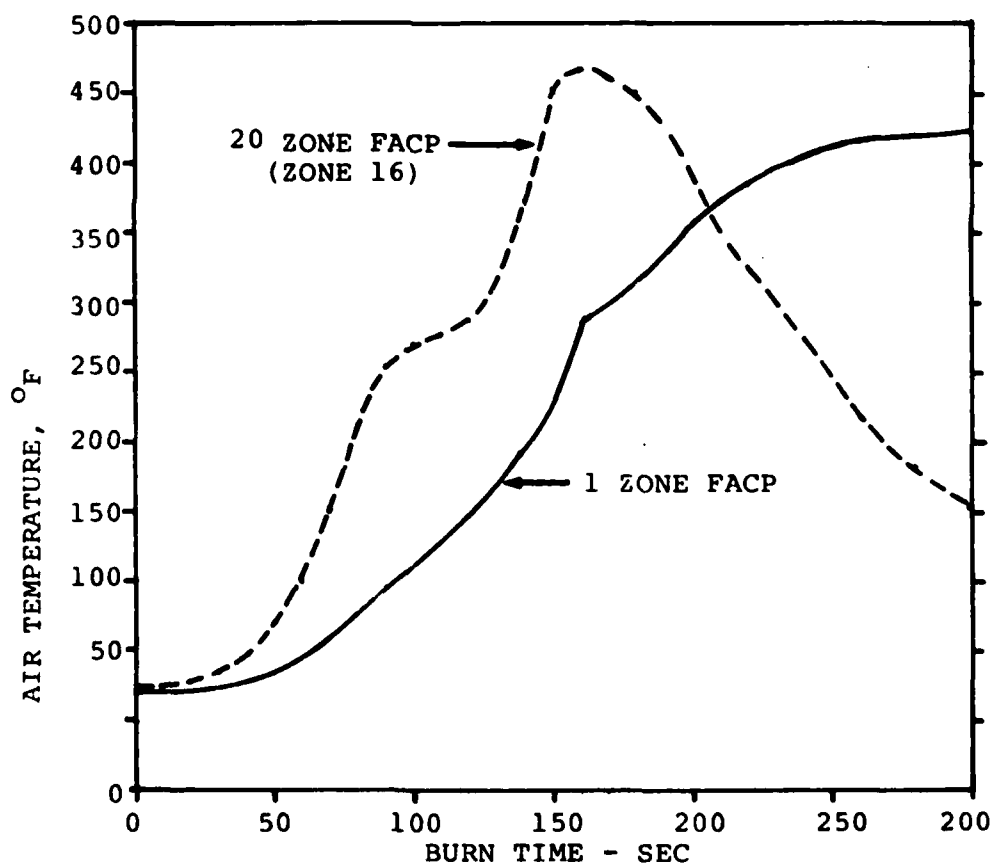


FIGURE 68. AIR TEMPERATURE COMPARISON - 1 ZONE FACP AT CFS EXHAUST AND 20 ZONE FACP AT ZONE 16 PANEL 3 AT 4.41 Btu/ft² SEC

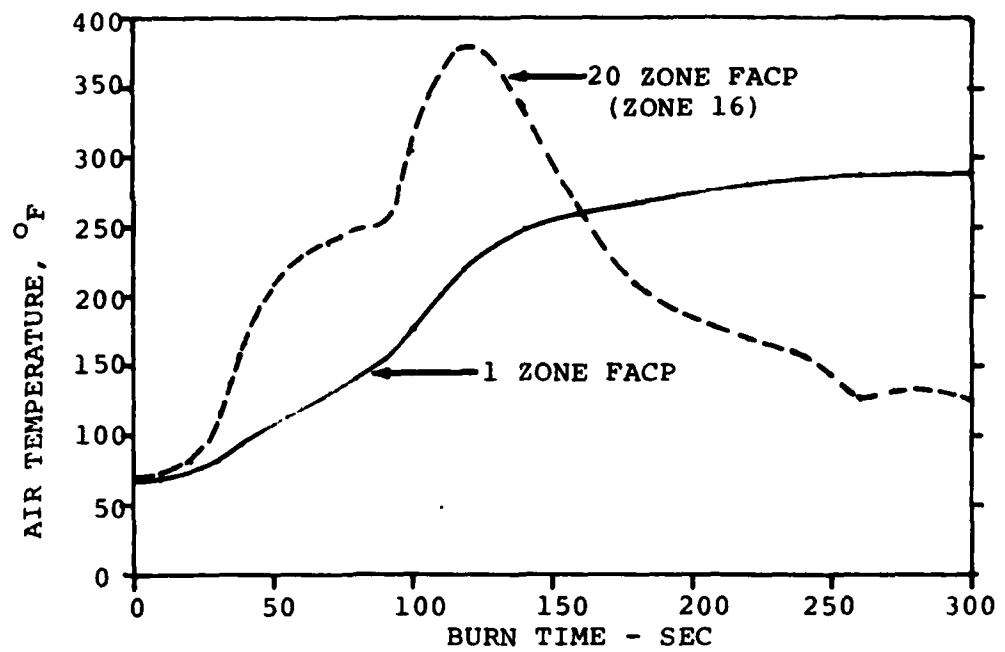


FIGURE 69. AIR TEMPERATURE COMPARISON - 1 ZONE FACP
AT CFS EXHAUST AND 20 ZONE FACP AT ZONE 16
PANEL 4 AT 4.41 Btu/ft² SEC

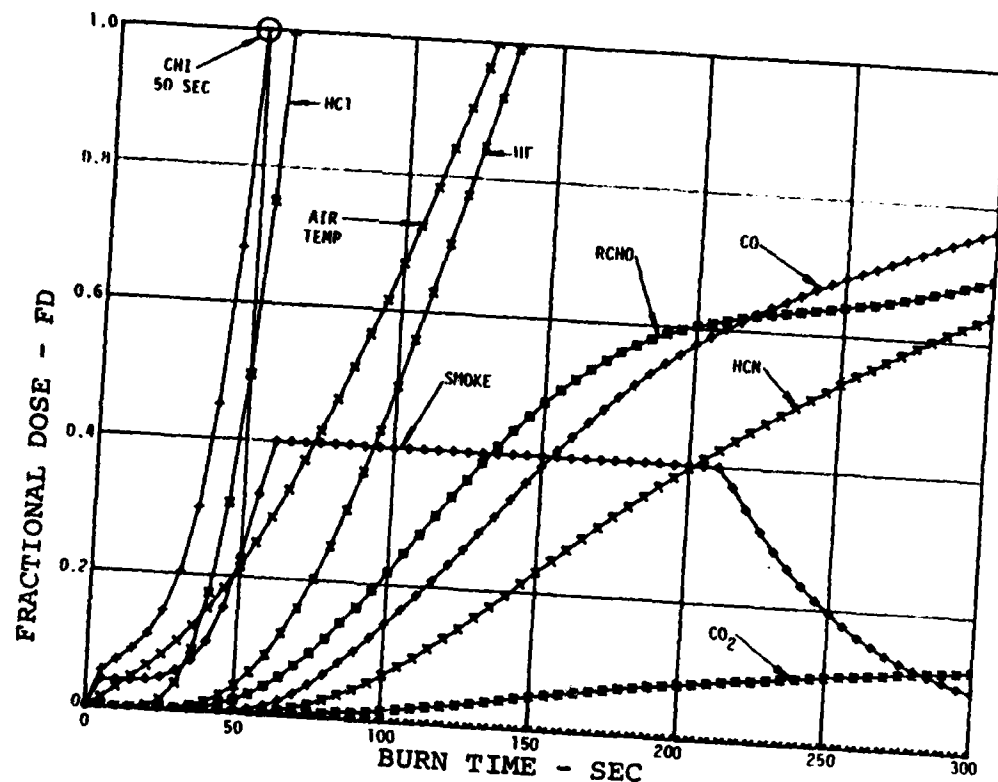


FIGURE 70. TWENTY ZONE FACP CHI AND FRACTIONAL DOSE PLOTS
PANEL 1 AT 4.41 Btu/ft² SEC

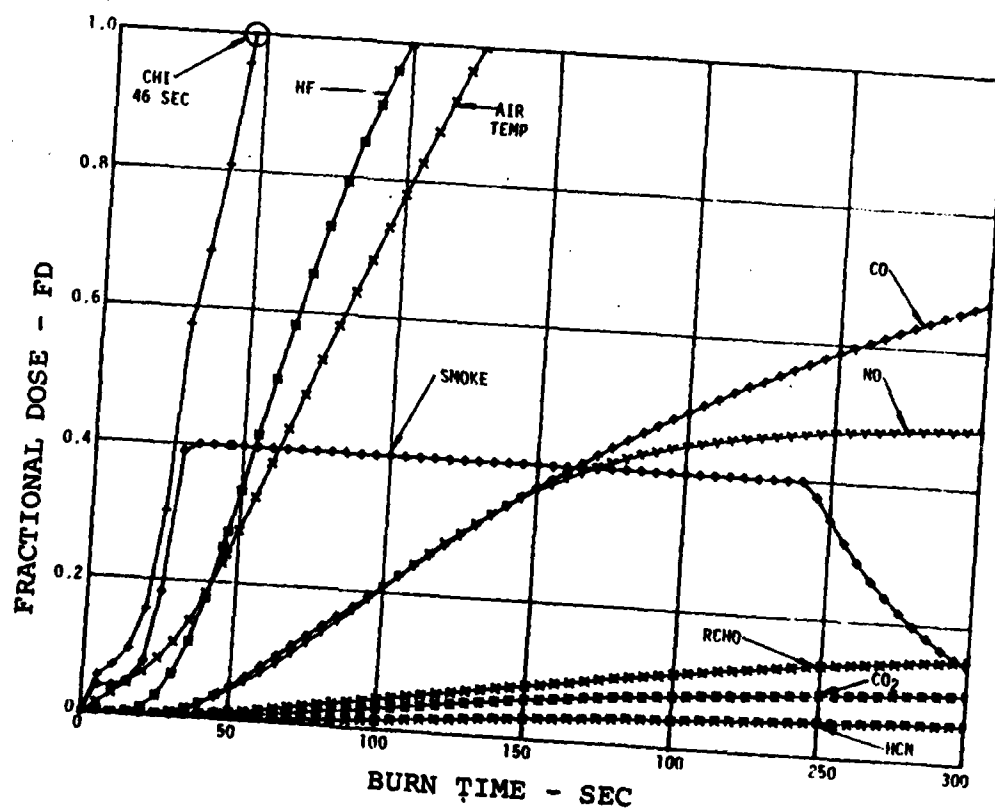


FIGURE 71. TWENTY ZONE FACP CHI AND FRACTIONAL DOSE PLOTS
PANEL 2 AT 4.41 Btu/ft² SEC

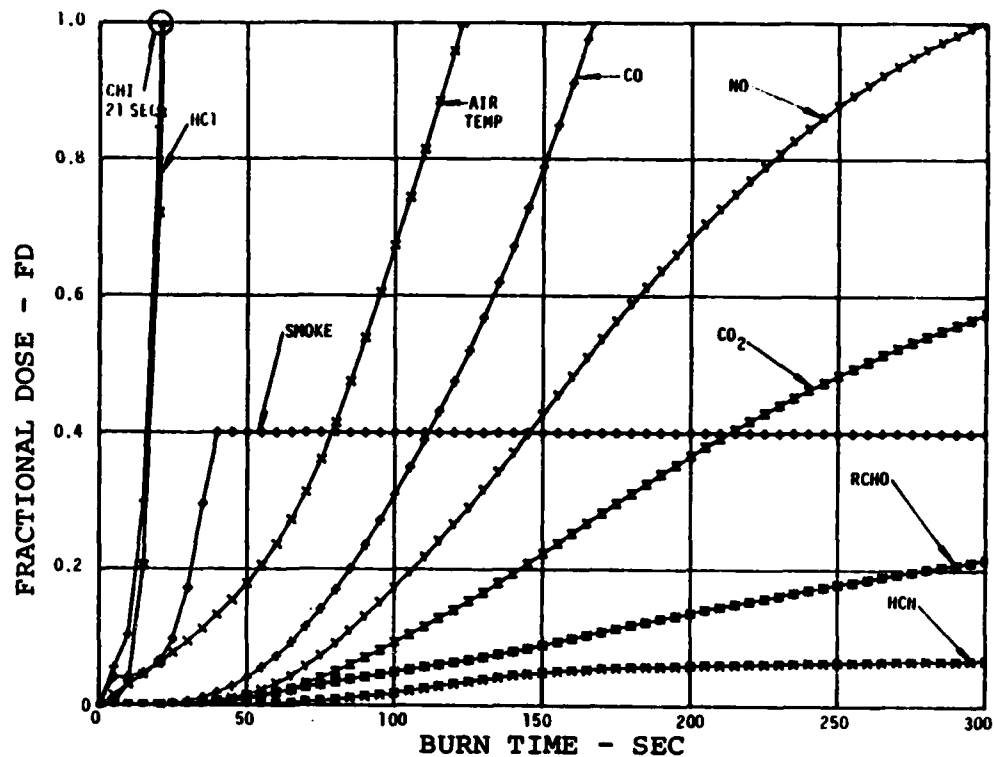


FIGURE 72. TWENTY ZONE FACP CHI AND FRACTIONAL DOSE PLOTS
PANEL 3 AT 4.41 Btu/ft² SEC

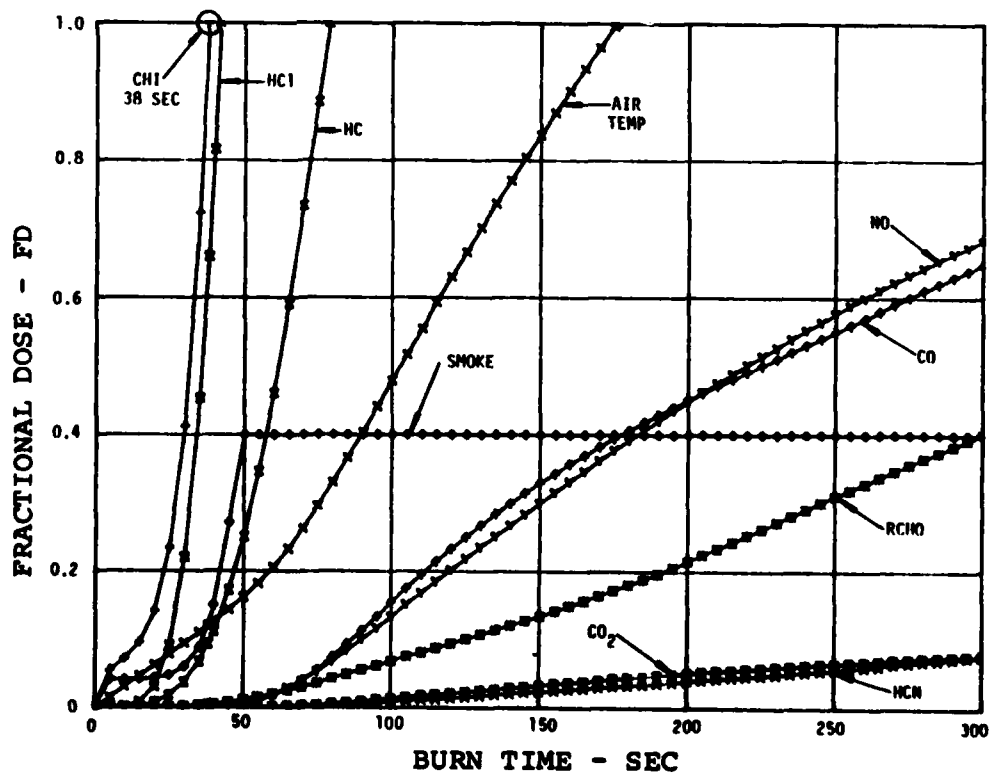


FIGURE 73. TWENTY ZONE FACP CHI AND FRACTIONAL DOSE PLOTS
PANEL 4 AT 2.2 Btu/ft² SEC

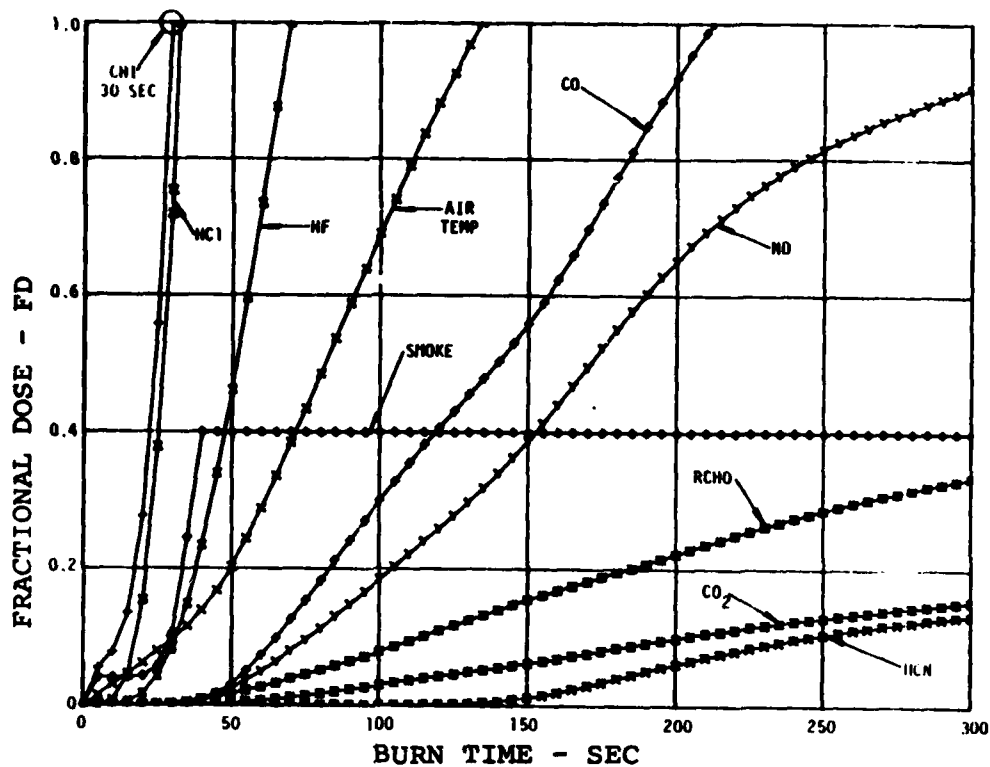


FIGURE 74. TWENTY ZONE FACP CHI AND FRACTIONAL DOSE PLOTS
PANEL 4 AT 3.08 Btu/ft² SEC

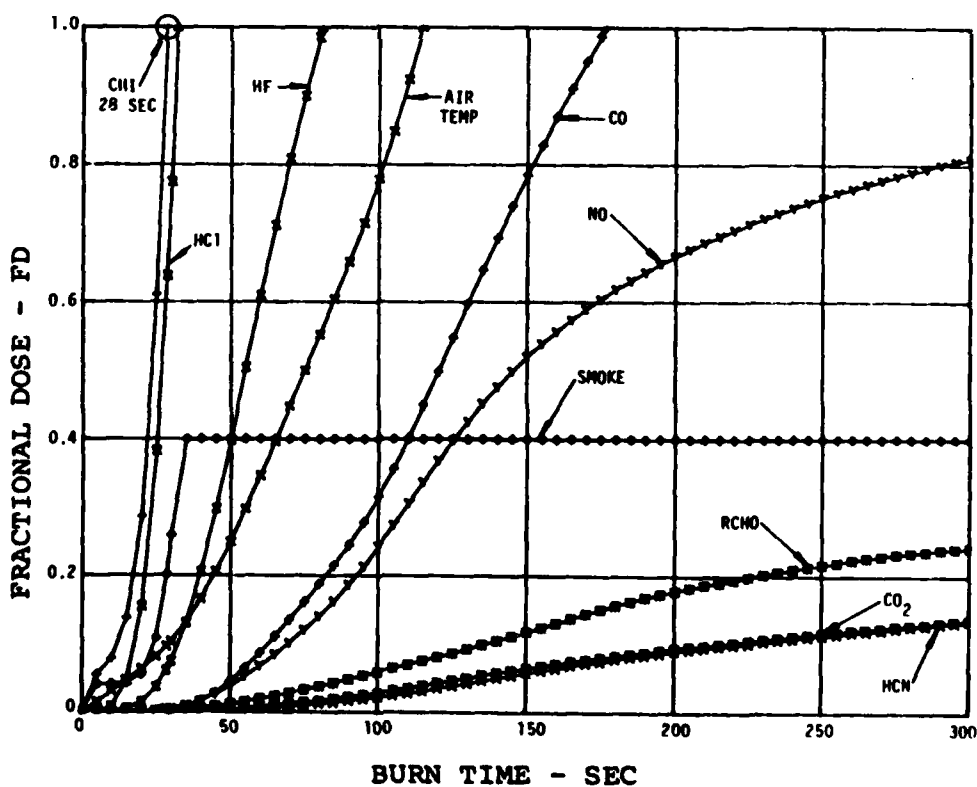


FIGURE 75. TWENTY ZONE FACP CHI AND FRACTIONAL DOSE PLOTS
PANEL 4 AT 4.41 Btu/ft² SEC

TABLE 20

SUMMARY OF CHI RELATIVE HAZARDS RANKINGS FOR
PANEL 1, 2, 3 AND 4 BY CHAS AND FACP

COMPUTER PROG.	BTU/FT ² -SEC FLUX & CHI VALUES *	PANEL NO.			
		1	2	3	4
1 ZONE PROGRAM	4.41 CHI, $\sum FD_i = 1$ $\sum FD_i$, 300 SEC RELATIVE CHI RANKING	68 (22) 2	80 (3.7) 1	16 (414) 4	30 (32) 3
	3.08 CHI, $\sum FD_i = 1$ $\sum FD_i$, 300 SEC RELATIVE CHI RANKING	NOT TESTED	110 (2.6) 1	50 (42) 2	31 (29) 3
	2.2 CHI, $\sum FD_i = 1$ $\sum FD_i$, 300 SEC RELATIVE CHI RANKING	NOT TESTED	100 (3.2) 1	65 (19) 2	41 (18) 3
	4.41 CHI, $\sum FD_i = 1$ $\sum FD_i$, 300 SEC RELATIVE CHI RANKING	50 (55) 1	46 (5.1) 2	21 (932) 4	28 (73) 3
	3.08 CHI, $\sum FD_i = 1$ $\sum FD_i$, 300 SEC RELATIVE CHI RANKING	** NOT TESTED	FACP NOT RUN	FACP NOT RUN	30 (70)
	2.2 CHI, $\sum FD_i = 1$ $\sum FD_i$, 300 SEC RELATIVE CHI RANKING	** NOT TESTED	FACP NOT RUN	FACP NOT RUN	38 (41)
20 ZONE PROGRAM AT ZONE 13	4.41 CHI, $\sum FD_i = 1$ $\sum FD_i$, 300 SEC RELATIVE CHI RANKING	50 (55) 1	46 (5.1) 2	21 (932) 4	28 (73) 3
	3.08 CHI, $\sum FD_i = 1$ $\sum FD_i$, 300 SEC RELATIVE CHI RANKING	** NOT TESTED	FACP NOT RUN	FACP NOT RUN	30 (70)
	2.2 CHI, $\sum FD_i = 1$ $\sum FD_i$, 300 SEC RELATIVE CHI RANKING	** NOT TESTED	FACP NOT RUN	FACP NOT RUN	38 (41)

$\sum FD_i$ = Sum of measured fractional doses.

CHI = Escape time seconds at $\sum FD_i$ limit of unity.

* CHI Ranking Order = 1 to 4, least to most hazardous.

**Panel 1 tested in CHAS/SATS and CFS at one heat flux only.

well developed than those used for the other panel materials. The errors in quantitative measurements of HCl and HF for panel 1 probably account for the reversed ranking output by the 20 zone FACP.

Averages of the yields of gases, char yields (Y_c), heat and smoke release measurements for panels 1, 2, 3, and 4 were calculated from the data presented in Table 4 and 5. Based on the premise that higher hazards risk in crash fires are directly proportional to the rate and quantities of hazards released when tested at the selected heat fluxes, the apparent CHAS test rankings were as follows: At all heat flux levels the hazards release values rated the last 3 panels tested in the same order, i.e., 2, 4, 3 (least to most hazardous) except for smoke which reversed panels 3 and 4 in the ranking when tested at 3.08 Btu/ft² sec heat flux.

Table 21 summarizes the CHI program hazards ranking comparisons of the panel materials based on the results from the test animals in the CHAS/SATS and CFS, and the single and twenty zone FACP CHI escape times. Rankings for panel 1 were listed only for the highest heat flux since tests at lower heat flux levels were not made.

The ranking orders listed in Table 21 for all panel materials based on animal tests show considerable variation from the 1 zone and 20 zone FACP results. While 3 of the methods (out of 5 used) indicated panel 1 was least hazardous, the 1 zone FACP and the CHAS analytical data ranked this panel 2nd. Panel 2 was least hazardous by the CHAS data and the 1 zone FACP. The 20 zone and 1 zone FACP rankings were based on a 4 second spread in CHI values and, as previously discussed, were too close to rank them either 1 or 2 with confidence.

The animal rankings were difficult to determine in the CFS tests, and depended largely on the location of the animals in the CFS. Only six animals were used in each test. Because biological endpoints (Ti's and Td's) were not observed at many of the locations inside the CFS during these tests, fine judgements in ranking could not be made. Therefore, the CFS animal rankings were highly subjective and were of limited value for validating the CHI methodology. However, the CFS animal rankings listed in Table 21 were judged from the incidence with which a Ti and Td occurred at any location and the relative values of the Ti's obtained for each heat flux test level.

The CFS animal tests did show that panel 3 was the most hazardous material. Ranking judgements for the other materials, using animal data, were much less reliable. The SATS rankings tracked more closely with the CHAS analytical results, i.e., 2, 4, 3 at the two lower heat flux levels. The CFS animals gave the same ranking order as SATS only at 3.08 Btu/ft² sec. It should be noted that contributions of thermal stress (air temperature) to the CFS animal Ti and Td endpoints were minimized by use of insulated chambers. This is not realistic in an actual fire and some of the differences in ranking between the animal and FACP may have been due to the absence of thermal stress.

Four of the five methods of ranking at 4.41 Btu/ft² sec indicated the wood panel 3 was the most hazardous (ranking = 4). At all heat flux test levels this material was ranked most hazardous (4) by the various measurements and test methods 10 out of 13 times (77%). Panel 2 was ranked the second least hazardous material (if panel 1 is ranked 1); 9 out of 13 times (69%), panel 4 was next most hazardous material (ranking = 3) 8 out of 13 times (62%).

The investigation clearly showed that the CHAS 1 zone FACP was the most

TABLE 21

SUMMARY OF CHI RELATIVE RANKINGS FOR ALL MATERIALS
BY THE CHAS/SATS, FACP AND CFS ANIMALS

HEAT FLUX	TEST	PHENOLIC PANEL 1	CEILING PANEL 2	WOOD VENEER PANEL 3	EPOXY PANEL 4
4.41 BTU PER FT ² SEC	FACP-CHI 20 ZONE	1	2	4	3
	1 ZONE	2	1	4	3
	ANIMALS SATS	1	2	3	4
	CFS	1 *	3 *	4	2 *
	ANALYTICAL CHAS	2	1	4	3
3.08 BTU PER FT ² SEC	FACP-CHI 20 ZONE	ND	2	4	3
	1 ZONE	ND	2	3	4
	ANIMALS SATS	ND	2	4	3
	CFS	ND	2 *	4	3 *
	ANALYTICAL CHAS	ND	2	4	3
2.2 BTU PER FT ² SEC	FACP-CHI 20 ZONE	ND	ND	ND	ND
	1 ZONE	ND	2	3	4
	ANIMALS SATS	ND	2	4	3
	CFS	ND	3 *	4	2 *
	ANALYTICAL CHAS	ND	2	4	3

* = BASED ON LIMITED DATA

ND = NOT DETERMINED, TESTED ONLY AT ONE HEAT FLUX

1,2,3,4 = ASSIGNED RANKING, LEAST TO MOST HAZARDOUS

practical of the methods investigated for rating the hazards potential of materials. The success of the method clearly is dependant on the proper selection of the combustion hazards to be measured (material chemistry) and the precision and accuracy of measurement of the hazards input into the FACP. Improvements in the test methodology could be achieved if the important toxic gases (HCl, HF, etc.) presently batch sampled and analyzed, could be monitored in real time.

Because of the obvious direct relationship of the total gas evolution from materials to the char yield, Y_c , it has recently been suggested (Reference 20) that Y_c determined by anaerobic thermogravimetric analysis is the only determination required to rank a material. While this approach, at face value, may appear to have merit, it should not be accepted without reservations. Many thermogravimetric instruments will accept only 5-15 milligram samples. This causes a very serious difficulty in that composited aircraft materials with many different resin constituents impregnated in layers of fiberglass can not be adequately sampled for such tests. The results are highly dependent on the validity of the sample. Another unrealistic feature of testing under anaerobic conditions (nitrogen or helium atmospheres) is the difference in weight loss response of a material as compared to actual fire environments in which air (oxidative pyrolysis) is involved.

The consistency of the CHAS data under the higher heat flux levels suggests that the method might be simplified. This approach is tempting, but may not provide an adequate measure of a material's fire response. However, it may be possible to simplify the CHI methodology as represented by the CHAS-single zone computer program by monitoring smoke and heat release rates and several combustion product gas release rates.

V. SUMMARY OF RESULTS

CHI LABORATORY METHODS

A methodology has been developed and demonstrated that will rank an aircraft cabin material as a Combined Hazards Index (CHI) calculated from the rates of heat, toxic gases, and visible smoke generated by a material.

1. The laboratory test apparatus, described as the Combined Hazards Analyses System (CHAS), consisting of an integrated system of commercially available instrumentation was developed to rate materials using a standardized ten minute test.
2. CHAS test costs were reduced by computer augmentation for data acquisition capability was developed for 10 hazards measurement instruments at the rate of 60 data points for each instrument per minute for burn tests up to 30 minutes duration.
3. Computer programs were written to transfer CHAS data to standard IBM 370 tapes for a Fortran Fire Analysis Computer Program (FACP) which predicts a cabin fire hazard environment from laboratory tests and calculates a CHI.
4. The heat release rates were measured by use of a fast response oxygen monitor and oxygen consumption calorimetry. This method avoided the inherent thermal lag of the differential thermopile and the heat absorption in the HRR chamber walls affecting the measurement.
5. Provision for syringe gas sampling, incorporated into the CHAS, was successfully used to analyze the combustion products for which real time instrumentation was not available (HCl, HC, RCHO).
6. It was estimated that materials fire response parameters, under ideal test conditions, measured in real time by the CHAS, may be expected to agree with each other within 2-9% for repeat tests.
7. Estimated relative errors for syringe sample/microchemical analyses varied from +6% to +7% for aldehydes or HF and +13 to +27% for HCl, depending on test sample size.
8. For the majority of hazards and at all 3 heat flux levels, CHAS measurements rated the panels from best to worst as follows: ceiling panel (2), phenolic partition (1), epoxy partition (4), and older wood veneer panel (3).
9. A Single Animal Test System (SATS) was constructed and successfully integrated with CHAS to determine combustion product mixture toxicity.
10. Panel 3, the vinyl/wood faced honeycomb panel generated 3 to 4 times more heat than panel 2 and 1.5 to 2.3 times more heat than panel 4 in 5 minutes.
11. In panel 2, 3 and 4 CHAS/SATS tests, $1/T_i$ values significantly correlated with CO yields. Correlation coefficients varied from 0.969 to 0.976.

12. Correlation of the summed yield of the most toxic gases (excluding CO_2) from panels 2, 3 and 4 with $1/\text{Ti}$ values in CHAS/SATS resulted in correlation coefficients varying from 0.80 to 0.94, which was a poorer correlation than for CO alone.

13. CHAS/SATS Ti measurements correlated with the Ti 's predicted by the Crane formula for CO concentrations.

HUMAN HAZARD LIMITS:

Human hazard limits were established for temperature, toxic gases and smoke (visibility). These limits combined in the computer programs determine escape time (CHI) of personnel from a cabin.

1. Threshold limit values from industrial and acute exposure literature data were extrapolated to 5 minute human hazard limits.

2. The empirical hazards limit relationships employed in the Fortran Fire Analysis Computer Program can be updated when more accurate short term toxicity data becomes available.

FORTRAN FIRE ANALYSIS PROGRAMS:

Twenty zone and one zone computer programs were developed to predict cabin environment and calculation of the CHI.

1. The 20 zone program is designed to predict temperature, smoke, gas concentrations and CHI in each of the 20 zones as a function of time.

2. The one zone program predicts the temperature, smoke, selected gas concentrations and CHI in the cabin as a function of time treating the cabin as a well stirred reactor.

FULL SCALE BURN TESTS:

A full scale burn test of all four panels was conducted to demonstrate to a reasonable degree the ability of the computer programs to predict the cabin environment.

1. Four 4 X 6 ft current and previously used wall and ceiling panels from commercial aircraft were fire tested at 2.2, 3.08 and 4.41 $\text{Btu/ft}^2 \text{ sec}$ heat flux.

2. The first phenolic wall panel was only tested at a heat flux of 4.41 $\text{Btu/ft}^2 \text{ sec}$ and had a weight loss (normalized mass burning rate) lower than when burned in the CHAS.

3. The remaining three panel constructions exhibited lower weight loss (normalized mass burning rates) in the CFS in comparison with the corresponding tests in CHAS/SATS except in the low heat flux run of panel 3.

4. Thermally insulated polycarbonate boxes with rotating cages and vacuum pumps to draw CFS (cabin) atmosphere inside, were developed and proved to be the best approach for reducing thermal stress in CFS animal tests.

5. The animals in CFS tests ranked panel 3 most hazardous which correlated with CHAS/SATS and 1 zone FACP results. The other panel materials could not be ranked with confidence because of test variables and insufficient data (lack of positive Ti endpoints).

6. The HCl, HF, and RCHO concentrations measured at the CFS exhaust indicated losses by reaction and by absorption on surfaces and smoke. Losses of from approximately 13 to 50% below concentrations predicted by CHAS were observed and not accounted for by differences in mass burning rate.

7. The prediction of gas concentrations by the computer programs were higher than measurements made near the animal cages at the CHI point and at the exhaust outlet of the CFS. These differences were attributable to differences in mass burning rates of the panels in CHAS and CFS absorption or reaction and attenuation of gas concentrations in the CFS, variations in diffusional mixing of gases, and random flow dynamics.

8. The 1-zone and 20-zone computer predictions of air temperatures in the CFS were reasonably close taking into account CFS radiant panel contributions and delay times for hot gases to reach measurement points, and the differences in mass burning rates experimentally observed.

VI. CONCLUSIONS

1. The Combined Hazards Analyses System (CHAS) test methodology developed during this study provides extensive and repeatable information related to heat, smoke and toxic gases hazards of a single aircraft material under a possible range of controlled test conditions encountered in a post-crash fire.
2. The equipment and instrumentation needed to assemble the CHAS are commercially available. This apparatus appears useful for the development of new fire resistant cabin material systems. The CHAS concept allows assessment of not only the flammability of material systems, but as well, the interaction of smoke and toxic gases.
3. CHAS test costs (labor) exceeded currently used FAR 25.853 flammability and NBS smoke chamber materials test costs by a factor of two or three, depending on the number of gases assayed.
4. The concept of transforming all CHAS hazard measurements to a common denominator-escape time-by application of fire and human survival models provides a method of combining and weighing the relative importance of the various hazards.
5. The Combined Hazard Index (CHI) of a material proposed by this study is the calculated escape time for the test conditions used. The validity of the CHI calculation is dependent upon the validity of the CHAS test methodology, human survival model and mathematical fire model.
6. It was beyond the scope of this study to establish the relationship between the derived human survival model and true escape potential of humans in a fire environment. However, it should be recognized that the survival model used is a simplified model since it contains (1) estimated 5-minute survival limits, (2) assumed hyperbolic relationship between concentration and escape time for each toxic gas hazard, (3) an unrealistic treatment of the dangers of smoke obscuration and (4) an assumption that all hazards are additive.
7. The fire model developed in this study is a simplified semi-empirical model. The agreement between fire model predictions and large-scale test measurements was found to be reasonable for temperature and smoke but lacking for toxic gases.

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